5th International Workshop on Statistical Seismology:
Physical and Stochastic modeling of earthquake occurrence and forecasting
31 May – 6 June 2007, Erice Sicily

INGV

# Coulomb Stress Interactions: Supporting and Conflicting Evidence

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# Outline - problem formulation

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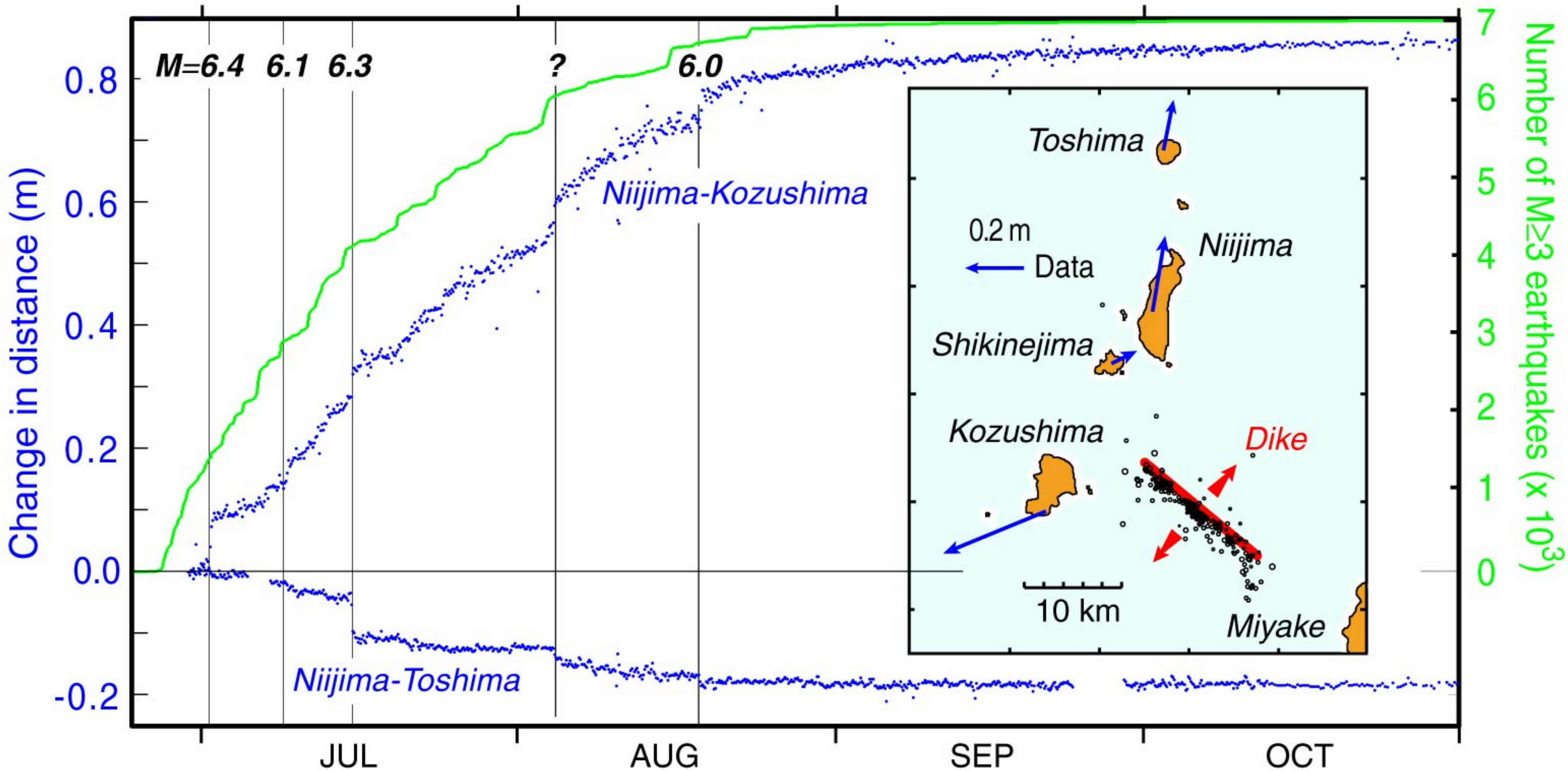
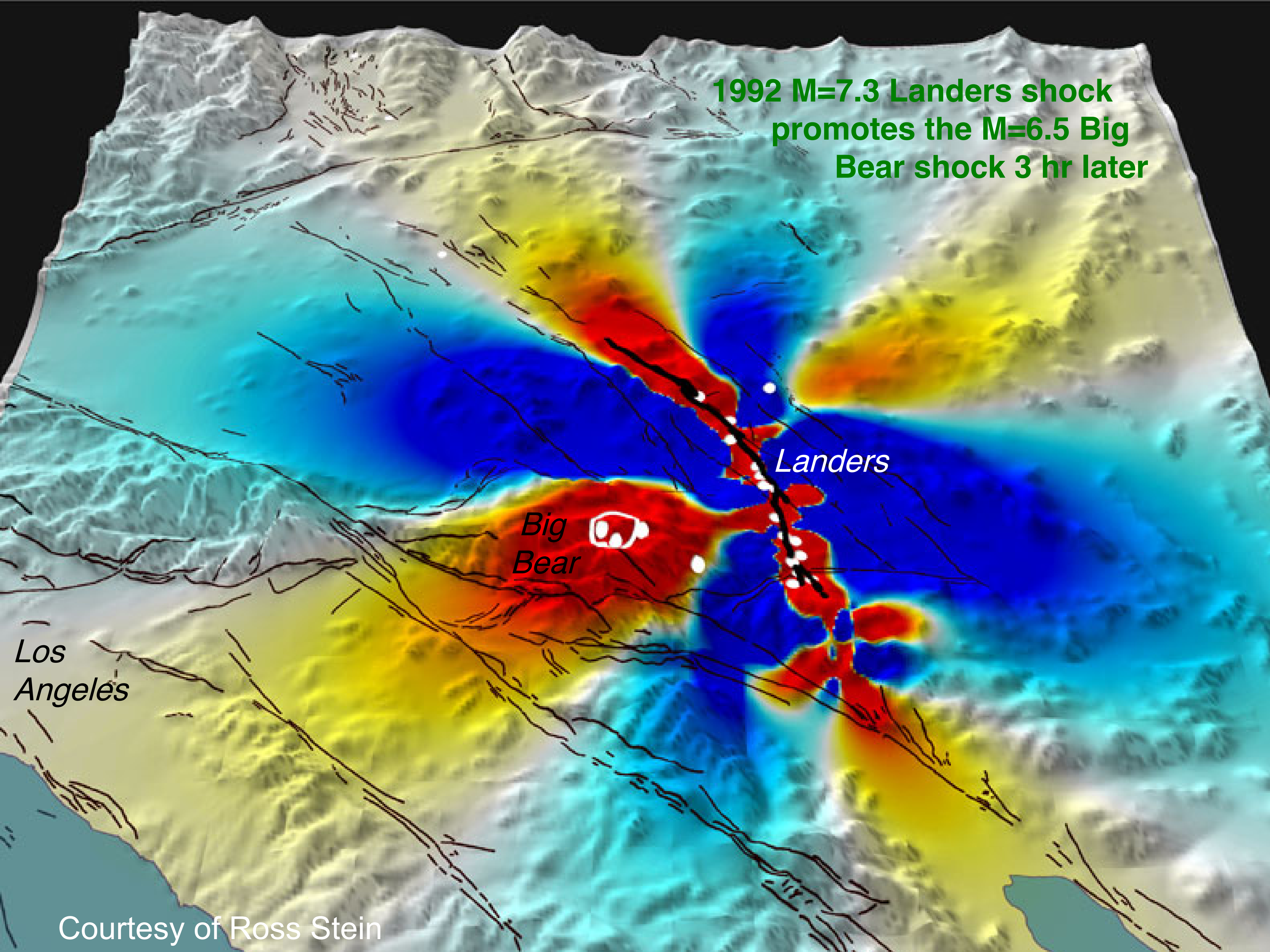
- Physical Motivations
  - Understanding fault interaction and earthquake triggering
  - Collecting information on earthquake nucleation through fault populations
  - Modeling spatio-temporal evolution of seismicity
- Hazard Goals
  - Assessing probabilities of occurrence for fault populations
  - Near-Real time assessment of aftershock probabilities (**SAFER**)
  - Single-fault probability for large magnitude earthquakes
- Prediction Tasks
  - Real Time forecasting
- Needs of validation of predictive methodologies (**NERIES**)

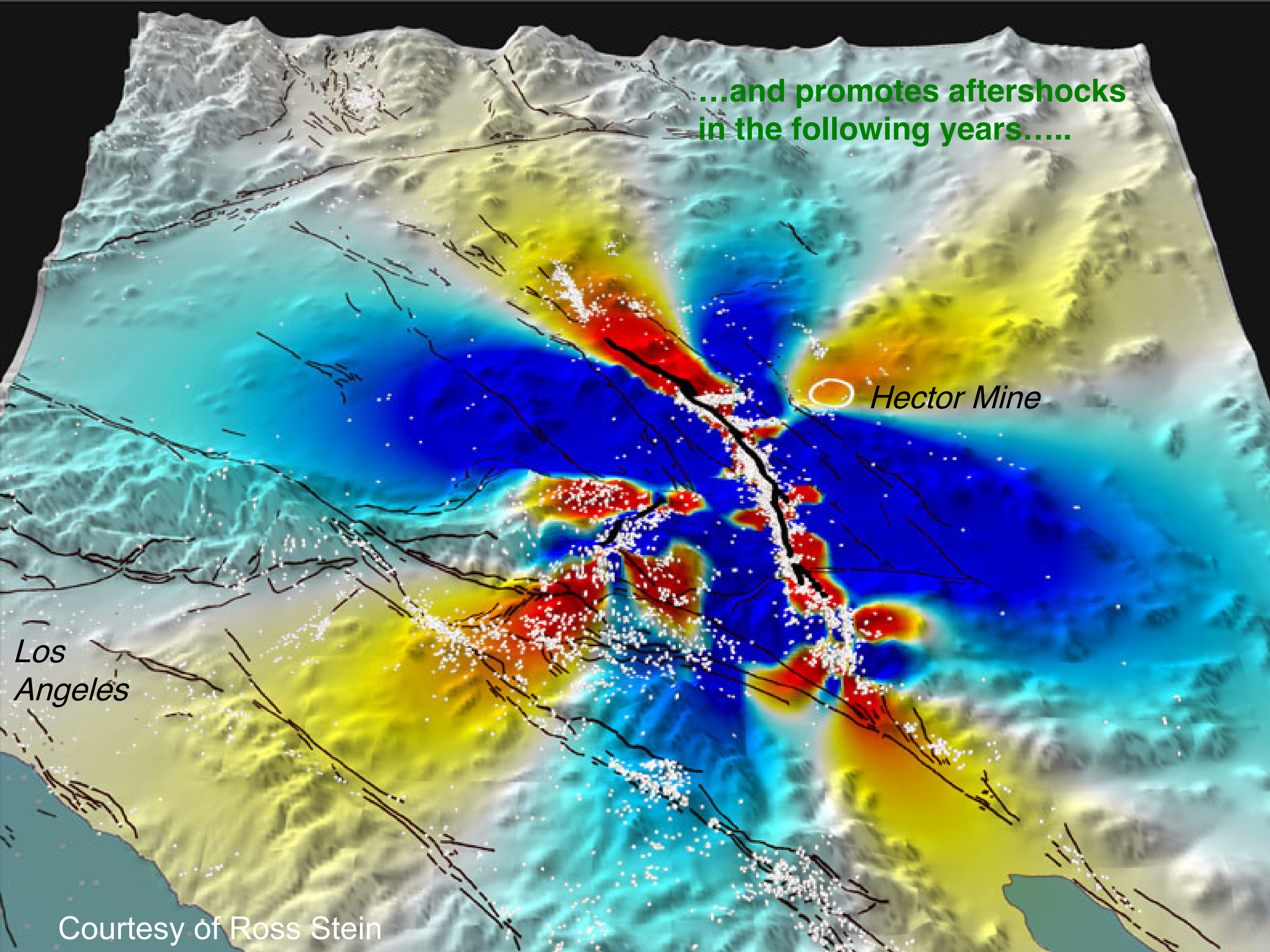
# 2000 Izu islands earthquake swarm

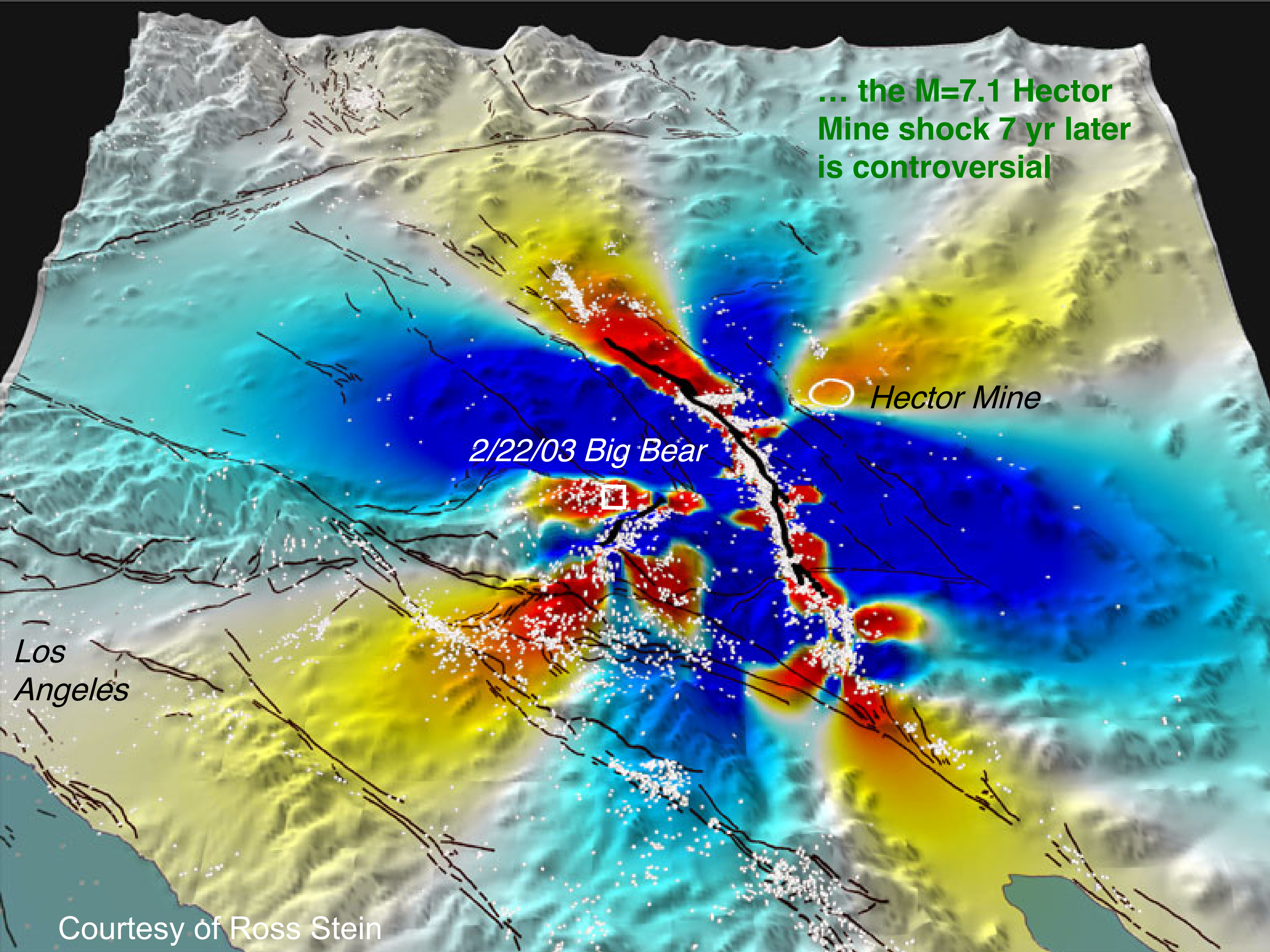
Dike expansion inferred as the deformation source




from Toda, Stein and Sagiya, Nature, 2002.


1992 M=7.3 Landers shock promotes the M=6.5 Big Bear shock 3 hr later
Landers
Big Bear
Los Angeles
Courtesy of Ross Stein


…and promotes aftershocks
in the following years…..
Hector Mine
Los
Angeles
Courtesy of Ross Stein



... the M=7.1 Hector Mine shock 7 yr later is controversial
Hector Mine
2/22/03 Big Bear
Los Angeles
Courtesy of Ross Stein

# Interaction through Coulomb Stress Transfer

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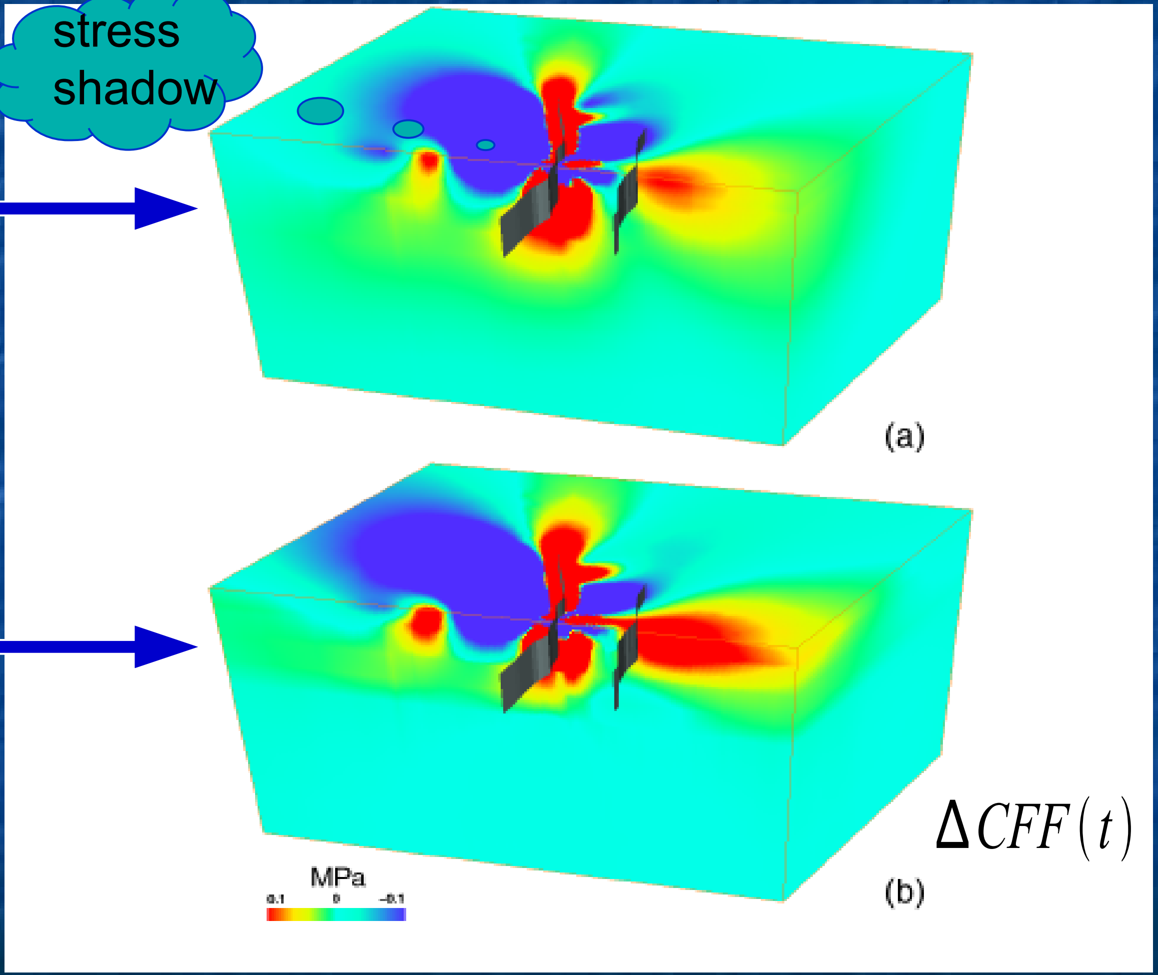
$$\Delta CFF = \Delta\tau + \mu\left(\Delta\sigma_n + \Delta P\right)$$

## Landers-Hector Mine

stress shadow

- **Coseismic (elastic)**
  caused by Landers, Big Bear, Joshua Tree earthquakes

- **Postseismic (elastic & viscoelastic)**
  immediately before the 1999 Hector Mine earthquake




$$\Delta CFF(t)$$

JGR Special Volume 2005: Stress Transfer, Earthquake Triggering and Time-Dependent Seismic Hazard

Cianetti S., Giunchi C. and M. Cocco, JGR (2005)

# Advantages of modeling Coulomb Stress changes

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- It accounts for extended sources and slip distributions on fault planes
- It accounts for complex geometry and focal mechanisms
- It accounts for the regional tectonic stress tensor
- It includes normal stress and pore pressure changes
- It is suitable to study tectonic coupling and mechanical interactions

Review papers: Harris, 1998; Stein, 1999; King & Cocco, 2001; Freed, 2005; Steacy et al., 2005;

# Main Motivations

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- The apparent correlation between Coulomb stress changes and the spatial distribution of aftershocks or seismicity suggests the possibility of making near-real time estimations of areas at risk of experiencing off-fault aftershocks or earthquakes and surrounding seismicity

- Coulomb stress perturbations and a frictional earthquake nucleation model allow the computation of changes in the rate of earthquake production and provide a physically-based model to study earthquake triggering

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# An earthquake nucleation model

- This explains the intrinsic (un-)predictability of earthquake occurrence

Time of impending earthquake

**Implies different length-scale parameters**

$$T_0 = F\left[C_i, \tau(t), \dot{\epsilon}(\xi, t), a, b, L, \theta_i(t), \sigma_n(t), p(t), ce_i\right]$$

Initial conditions

State variables

- Initial conditions account for fault maturity ( **m** )
- Stress history due to tectonic load and stress redistribution
- Strain rate account for accelerating failure process
- Constitutive parameters and state variables represent rheological properties of fault zones
- There are numerous other physical variables whose changes in space and time explain the intrinsic heterogeneity and complexity of earthquake process
- Earthquake dynamic rupture is a scale dependent process

# A frictional population model of seismicity rate change

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- A physically based model to predict seismicity rate changes accounting for fault frictional properties: the Dieterich 1994 model
- Faulting is governed by rate & state constitutive laws.
- Seismicity is modeled as a sequence of earthquakes or nucleating events.
- Timing of earthquakes is controlled by the stressing history and distribution of initial conditions over the population of nucleation sources (fault population).
- Earthquake clustering arises from sensitivity of nucleation times to induced stress changes.

change in failure time

$$t_{dl} = t_p - t_o = F\left[C_i, \tau(t), a, b, L, \sigma_n\right]$$

# Formulation for the Rate of Earthquake Production (Dieterich, 1992, 1994).

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We define the Coulomb stress changes as

$$\Delta CFF = \Delta\tau + (\mu - \alpha)\Delta\sigma_{eff}$$

The time of an earthquake at a source n is t = n/r, where r is the reference rate of seismicity (r=dn/dt).

The rate of earthquake production is:

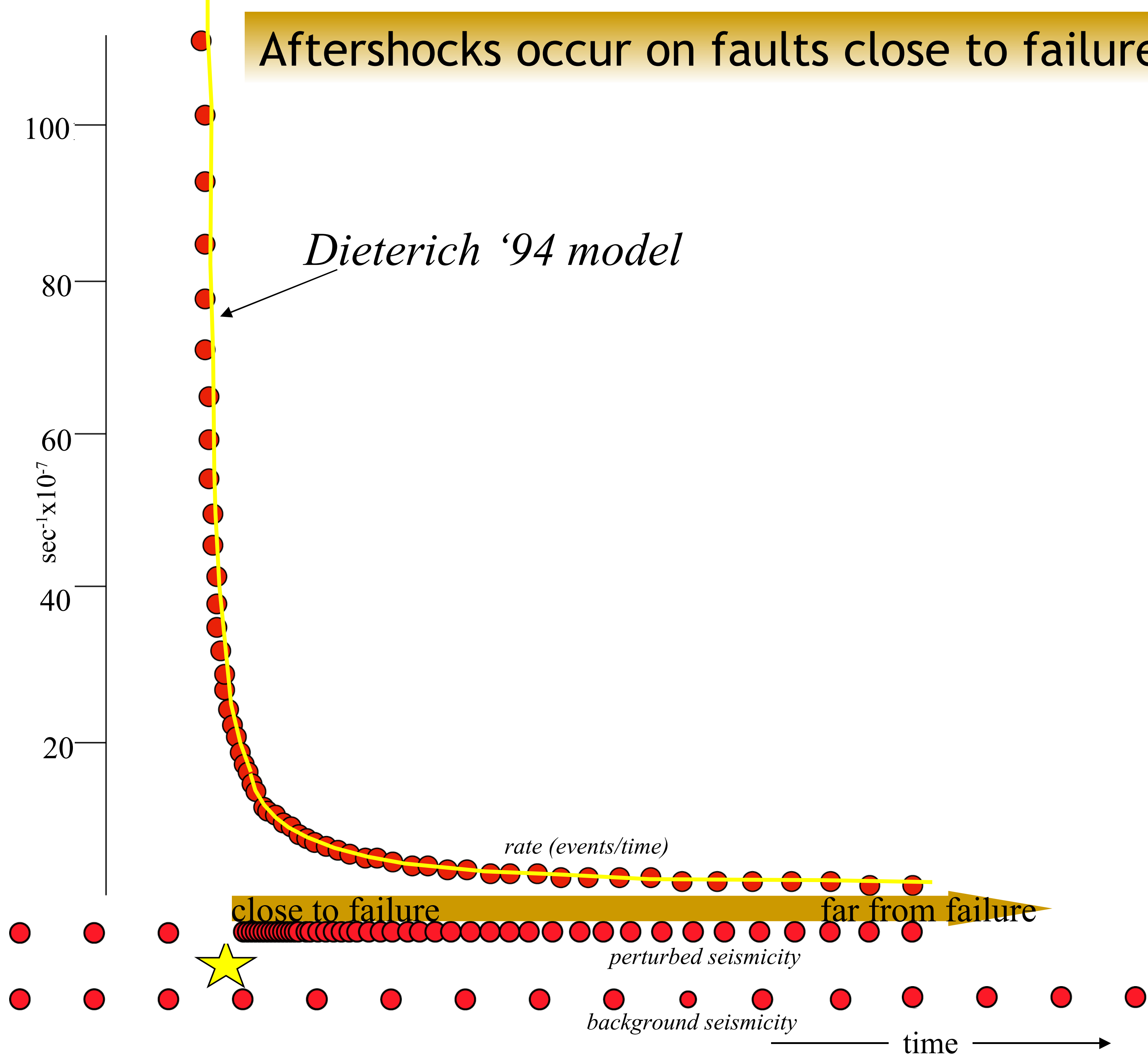
$$R = \frac{r}{\gamma\,\dot{\tau}_r}$$

An applied stress perturbation to the fault population modifies the seismicity rate through the evolution of the state variable given by:

$$\gamma_n = \gamma_{n-1}\exp\left(\frac{-\Delta CFF}{A\sigma}\right).$$

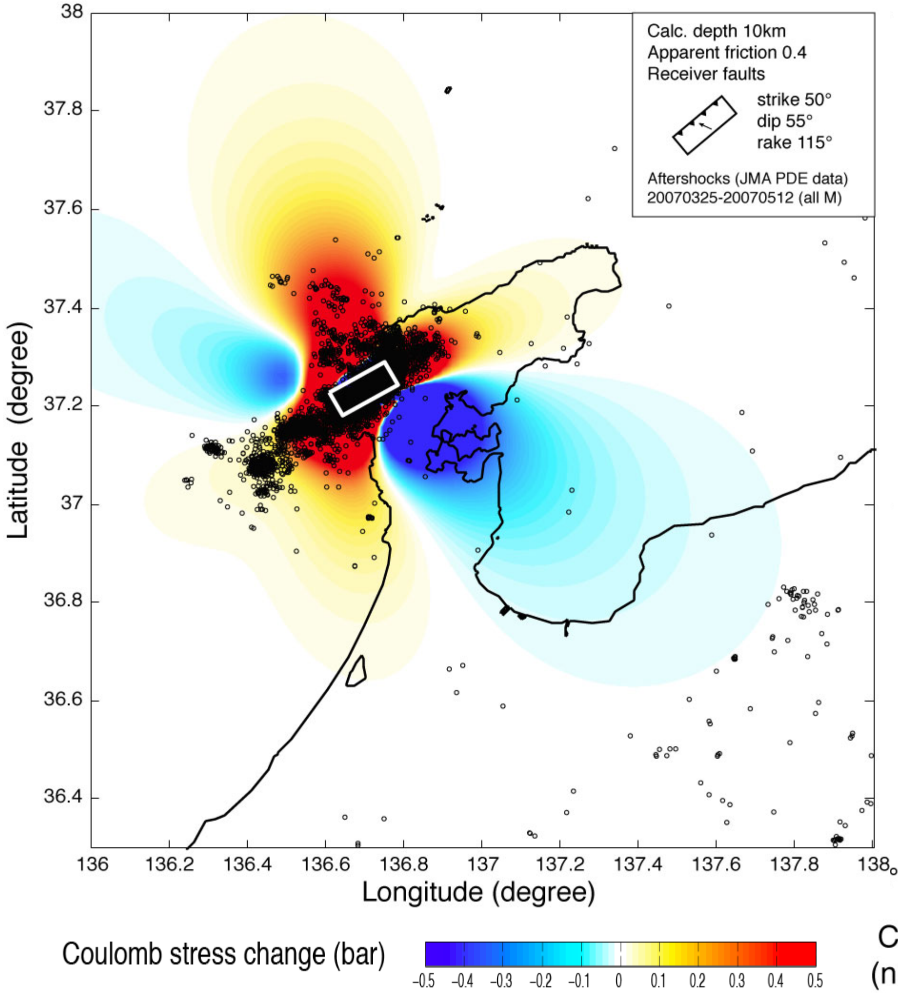
<u>The three main ingredients</u>: $r, \dot{\tau}_r, A\sigma$

# Aftershocks occur on faults close to failure.

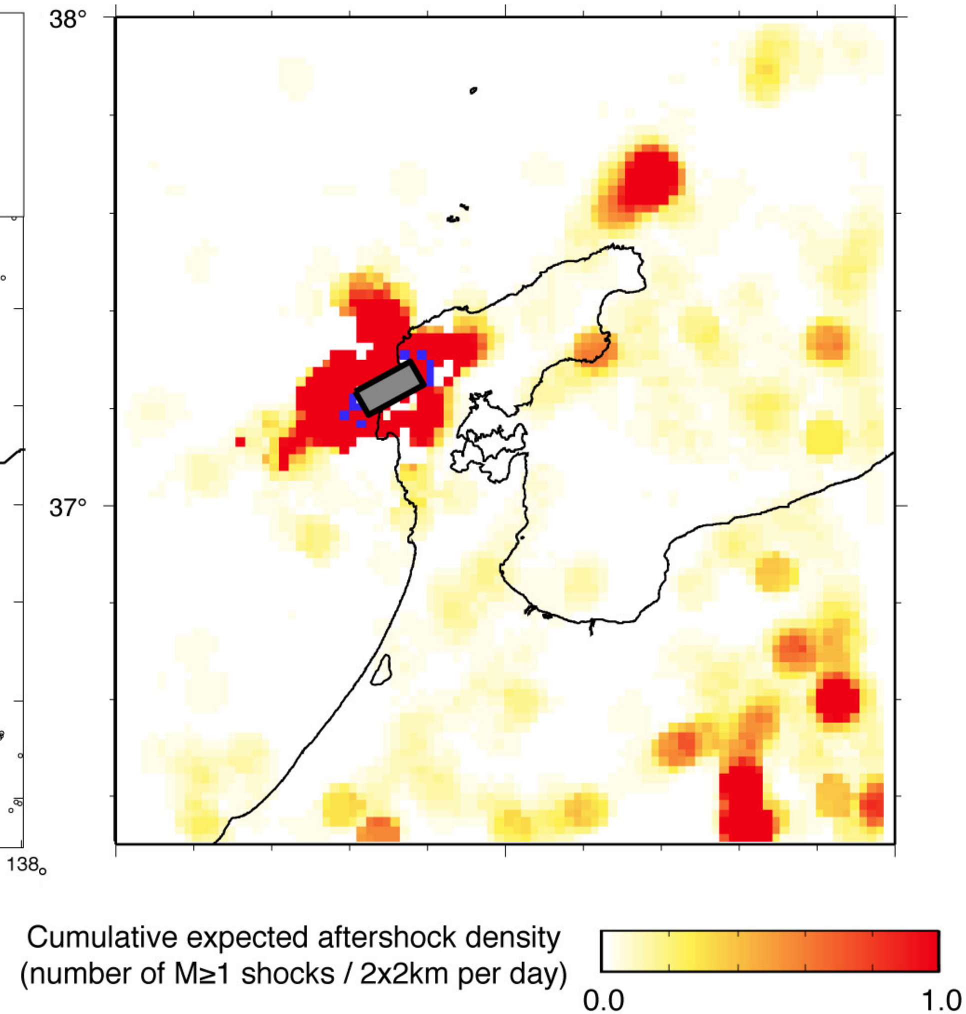


# Spatial forecasting of off-fault aftershocks: An example from M=6.9 Noto-Hanto Japan earthquake of 25 May 2007

## Simple coulomb calc. & aftershocks




## Rate & state prediction

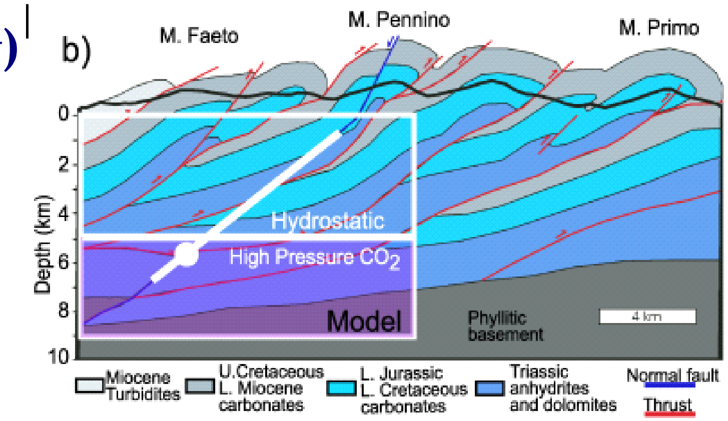


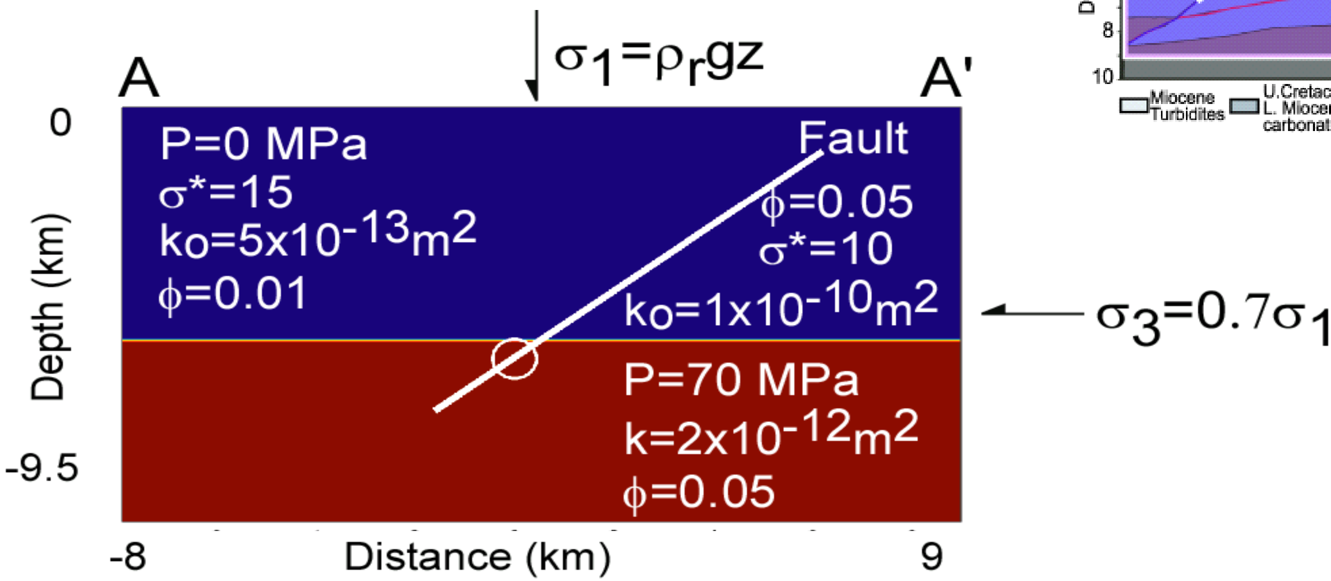

**Courtesy of Shinji Toda**

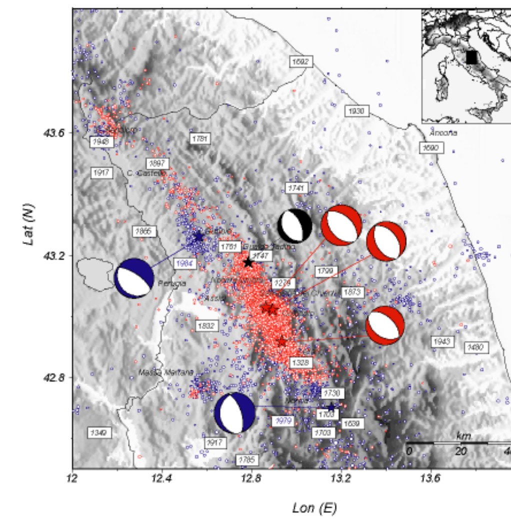
# Problems in modeling and interpreting Coulomb stress interactions

- Definition of stress shadows and their persistence ?
- Role of dynamic and static stress changes ?
- Other time-dependent relaxation processes?
- Contribution of secondary triggering ?
- Role of stress heterogeneity ?
- Definition & measure of reference rate of seismicity

# Poro-elastic effects: a study of the 1997 Umbria Marche (Central Apennines, Italy) region



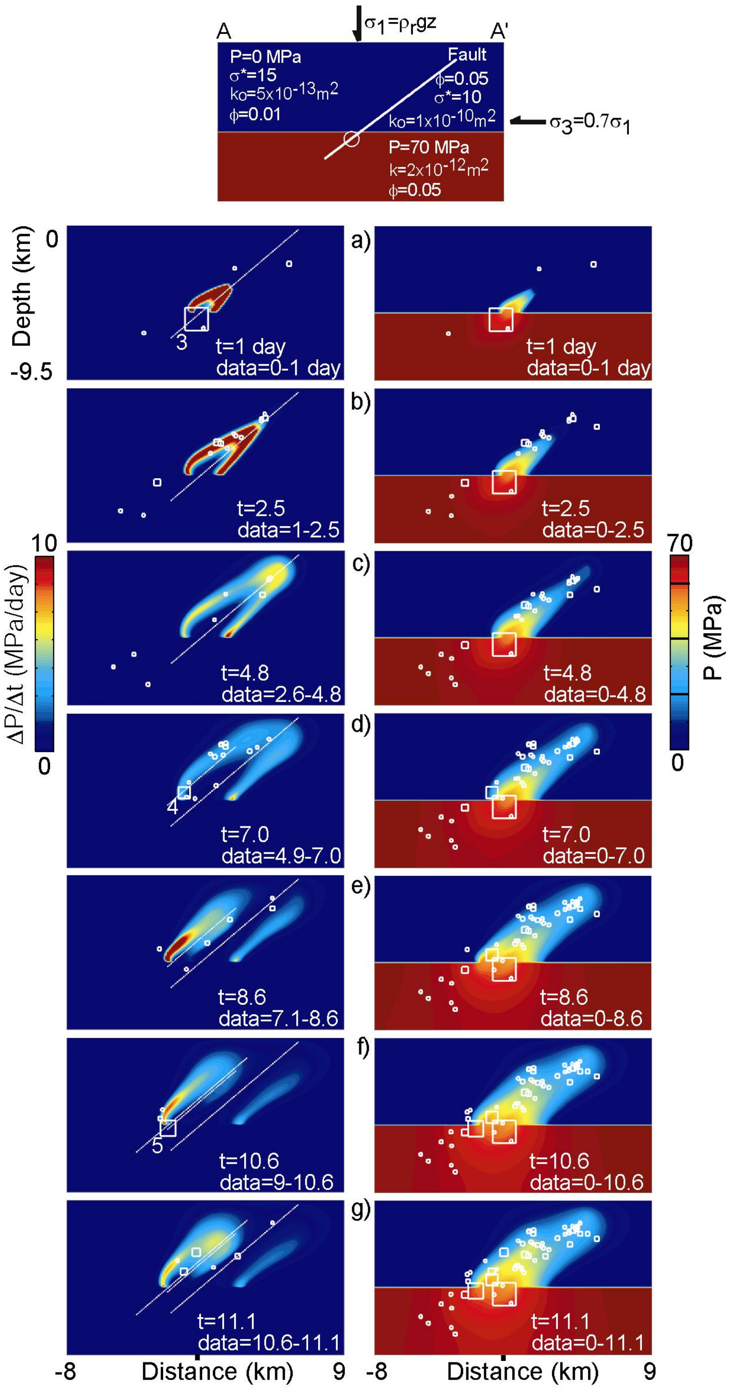



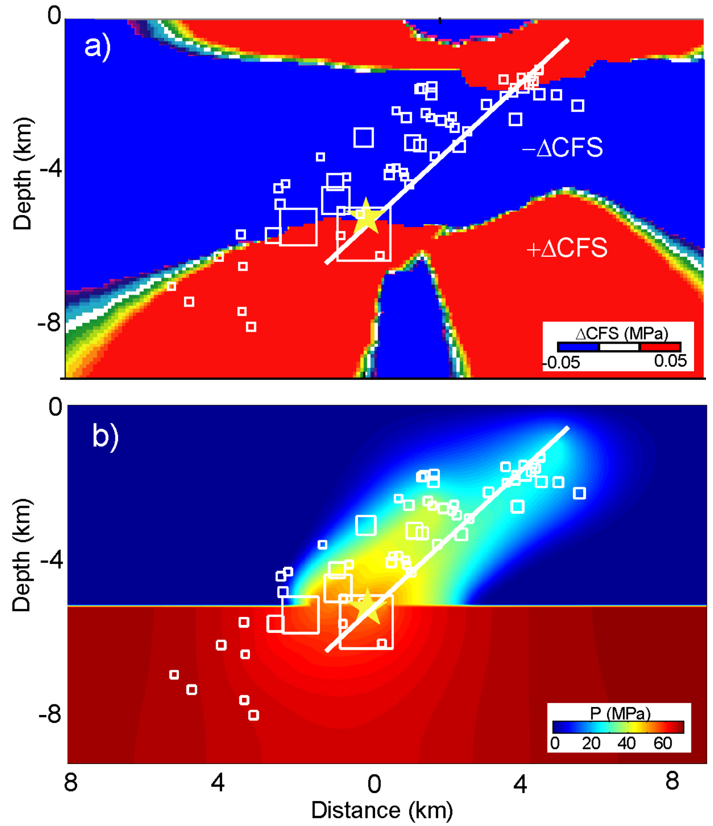




$$\frac{\partial P}{\partial t}=\frac{1}{\varphi(\beta_f+\beta_\varphi)}\nabla\cdot\left[\frac{k_o\exp\left(-\frac{\bar{\sigma}_n}{\sigma^*}\right)}{\eta}\nabla P+\Gamma\right]$$

**Miller et al., Nature, 2004**

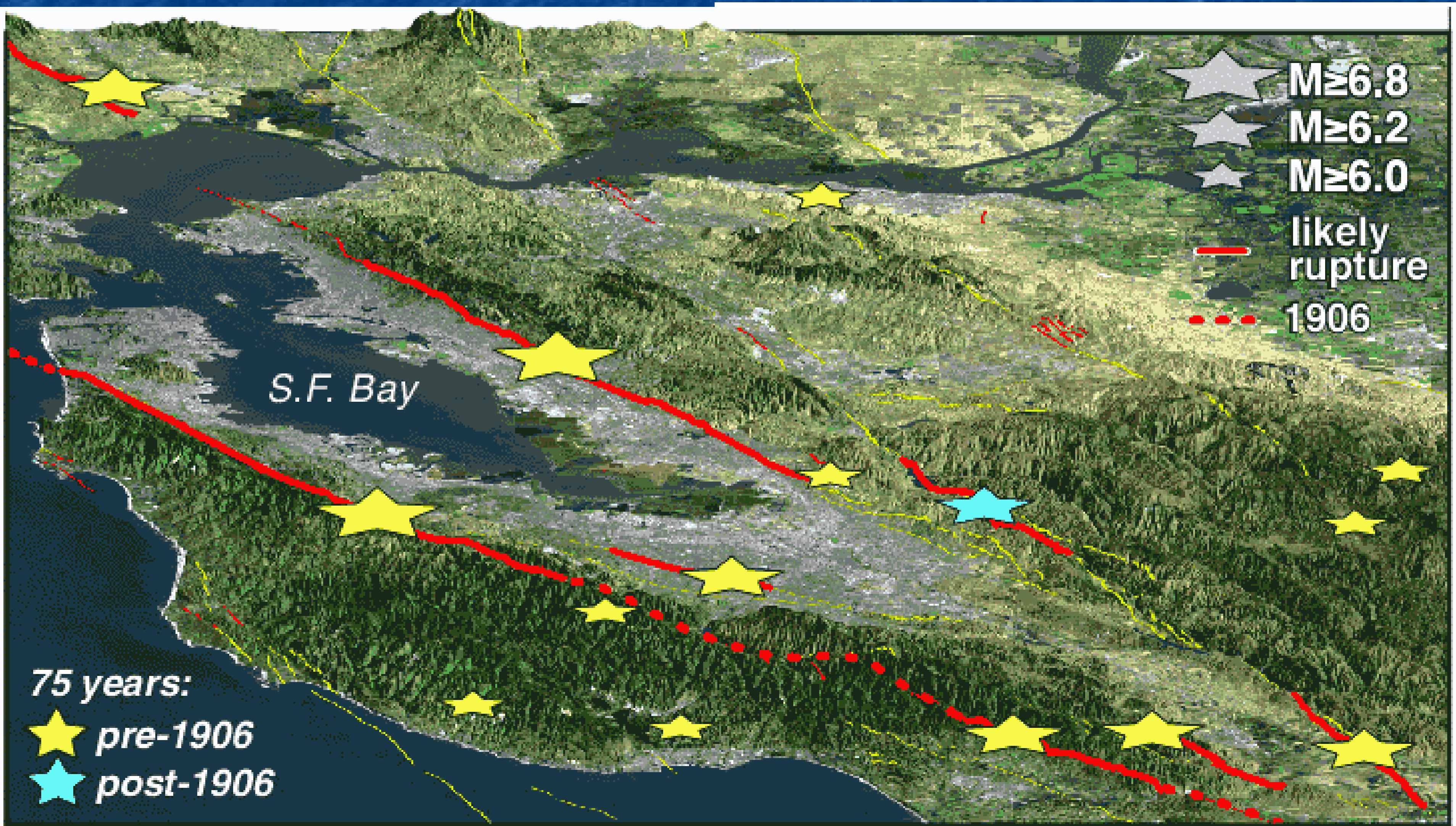
# Elastic Coulomb stress changes versus poro-elastic response

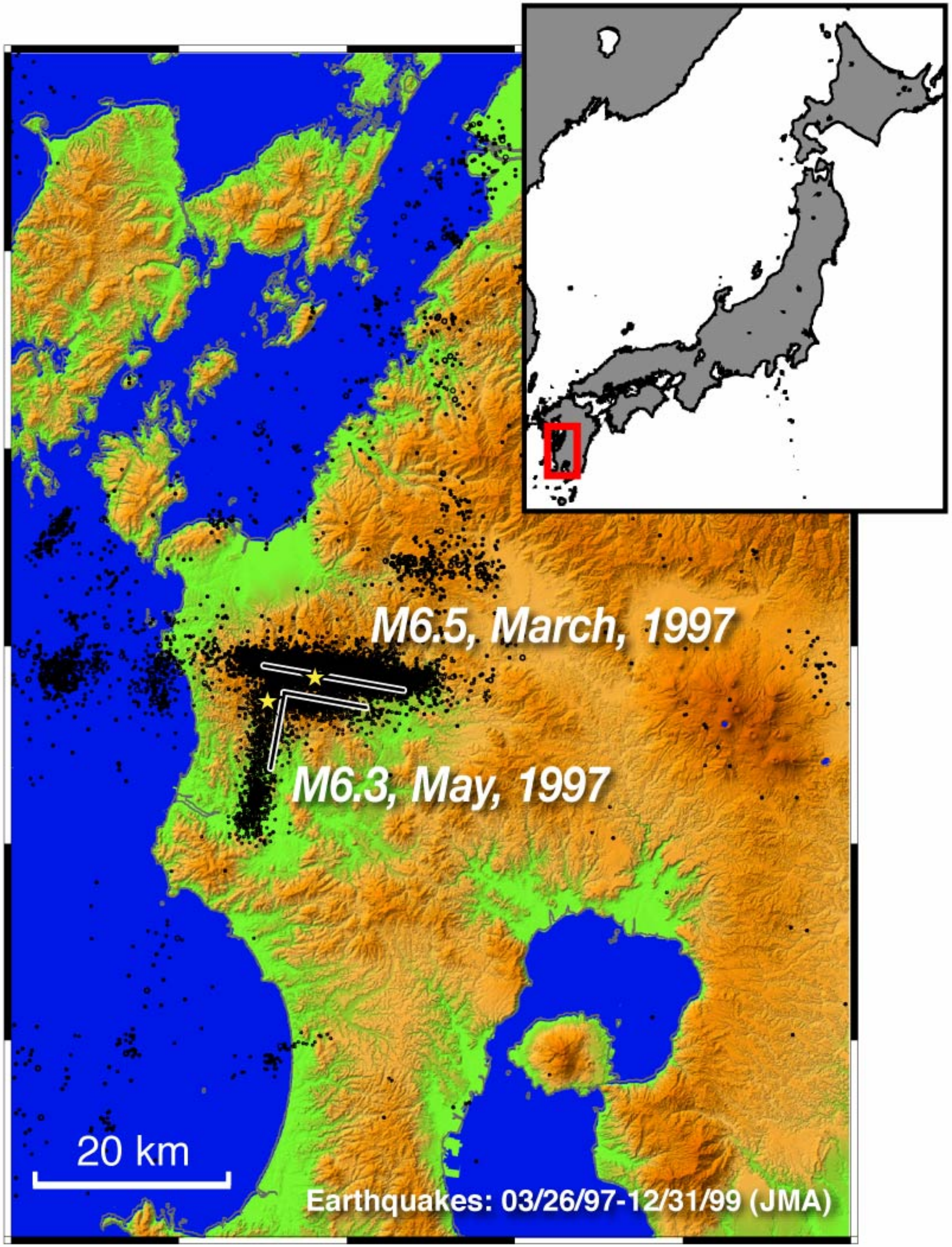



Miller et al., Nature, 2004

# Stress Shadows: Definition

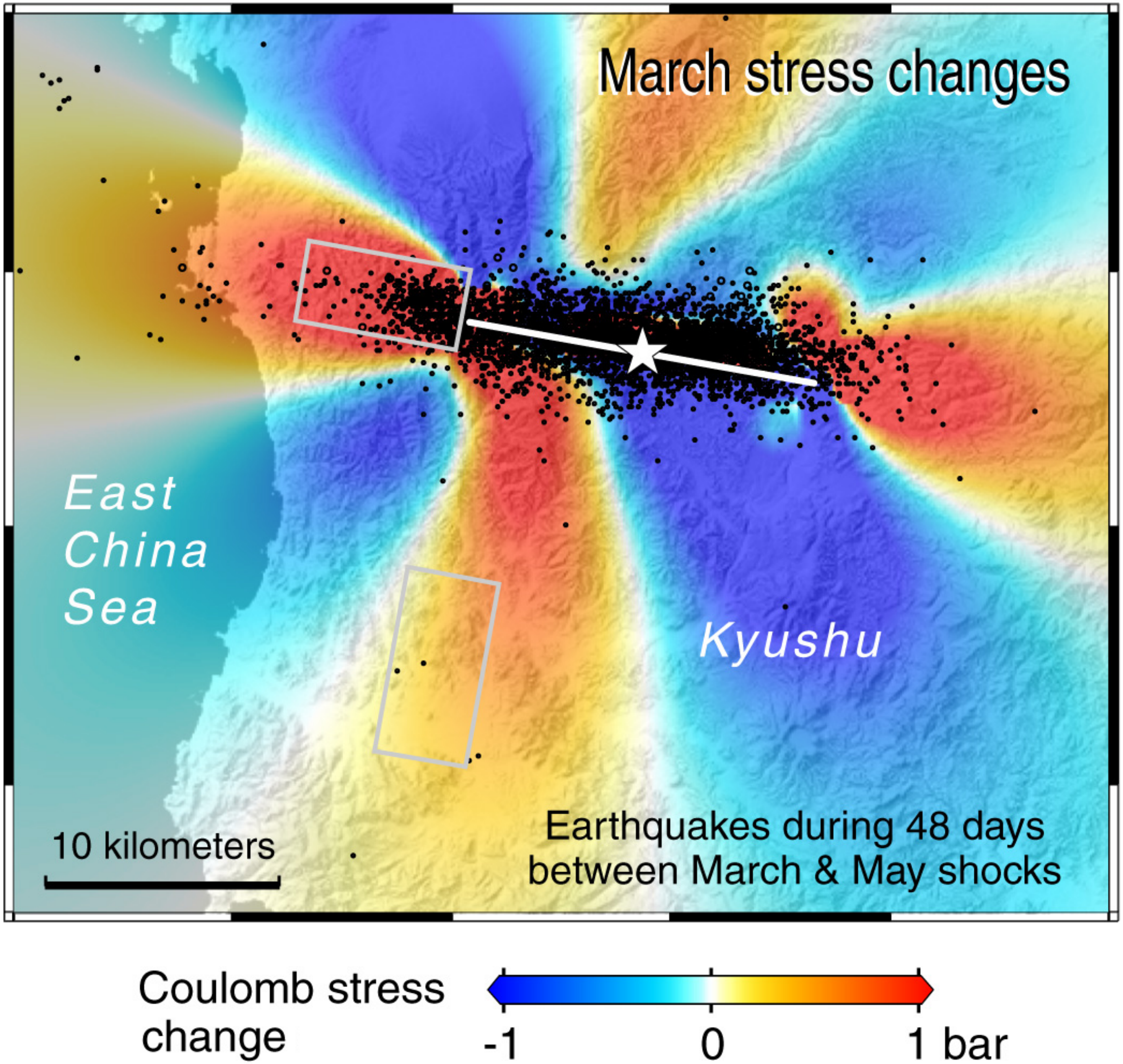





It is demonstrated that that stress triggers turn earthquakes on

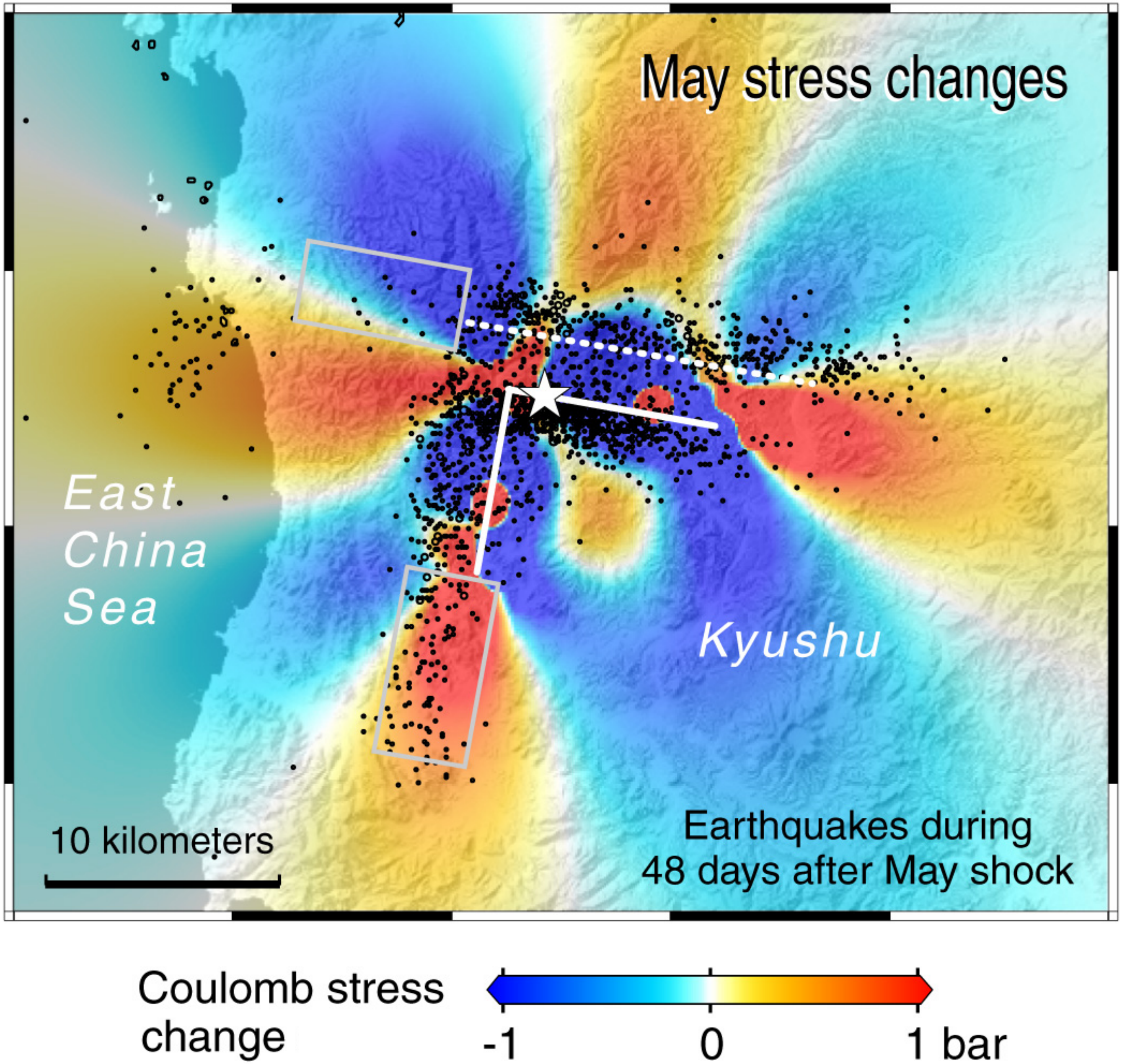
But can we demonstrate that stress shadows turn earthquakes off?

Toda & Stein, 2003




Off-fault aftershocks controlled by Coulomb stress changes

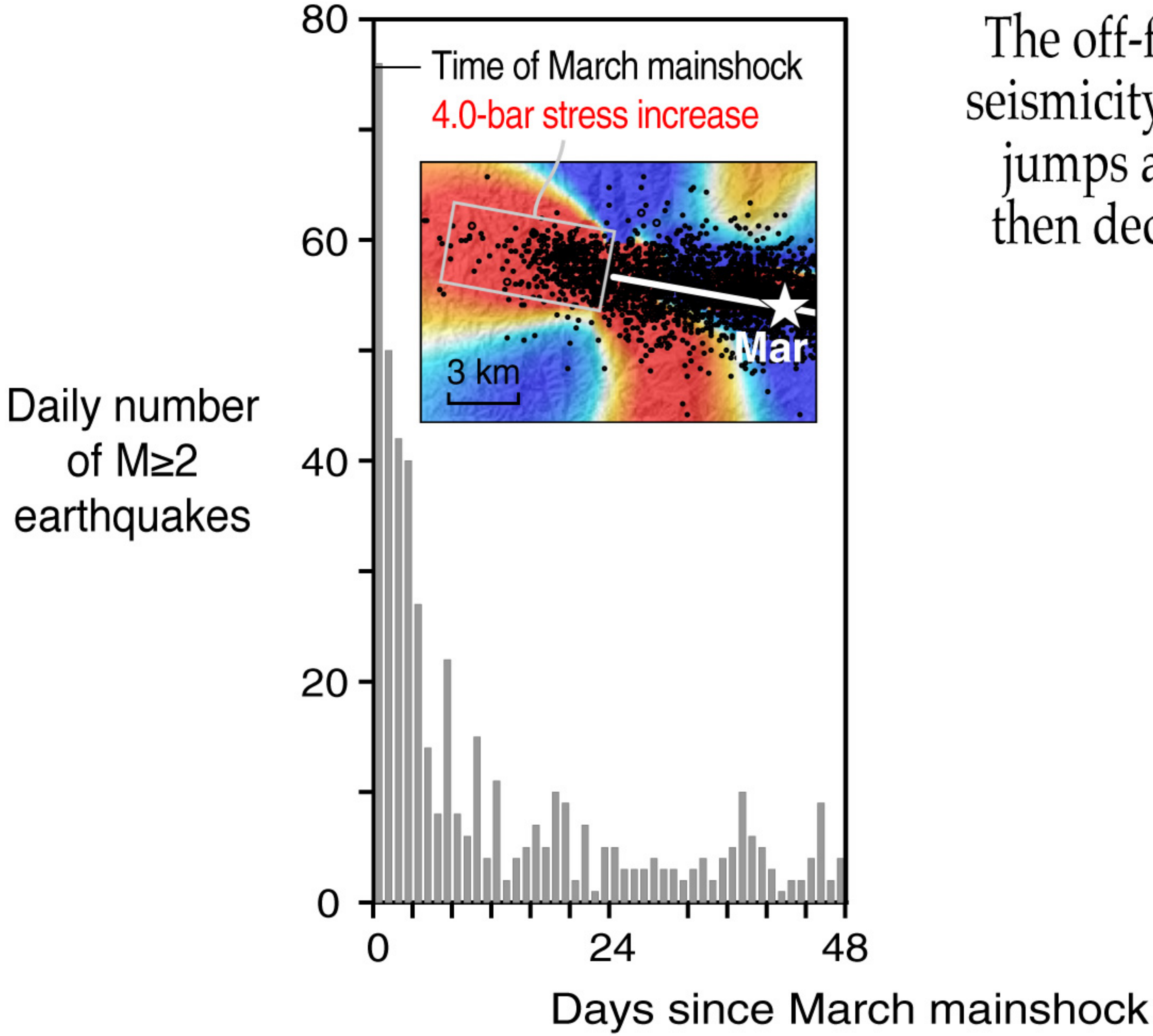
Toda & Stein, 2003



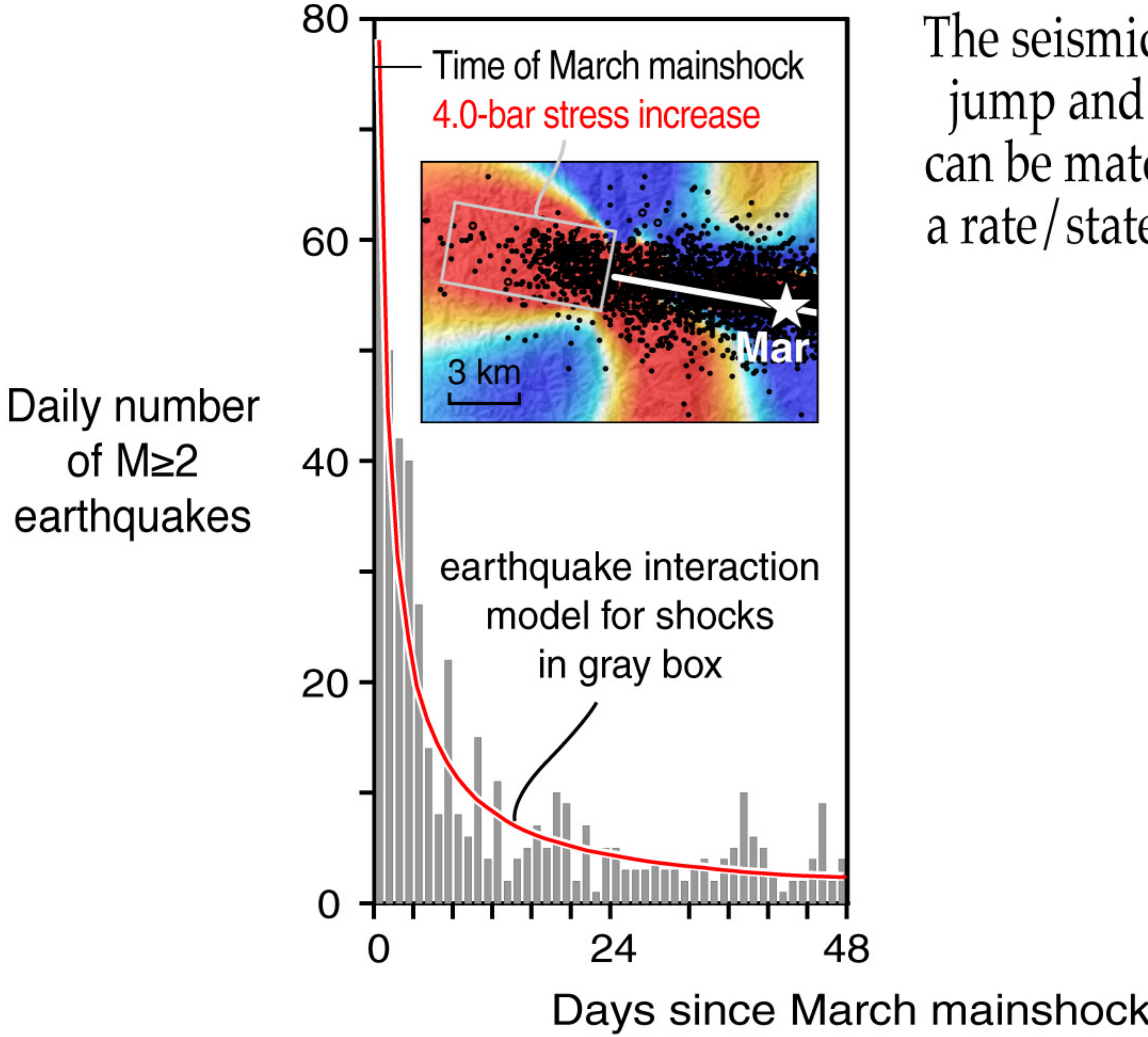

# Off-fault aftershocks controlled by Coulomb stress changes

Toda & Stein, 2003

# The off-fault seismicity rate jumps and then decays

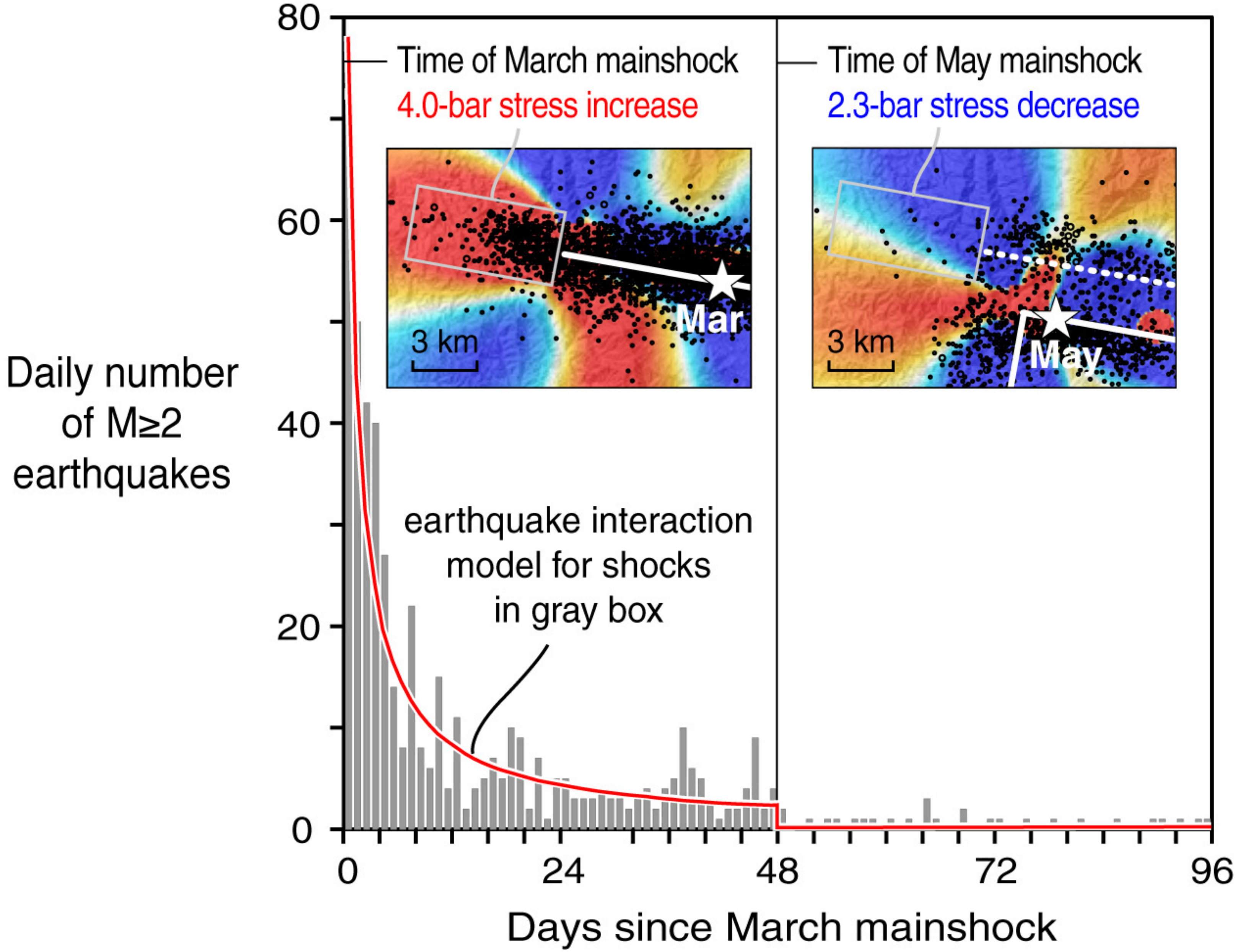



Toda & Stein, 2003

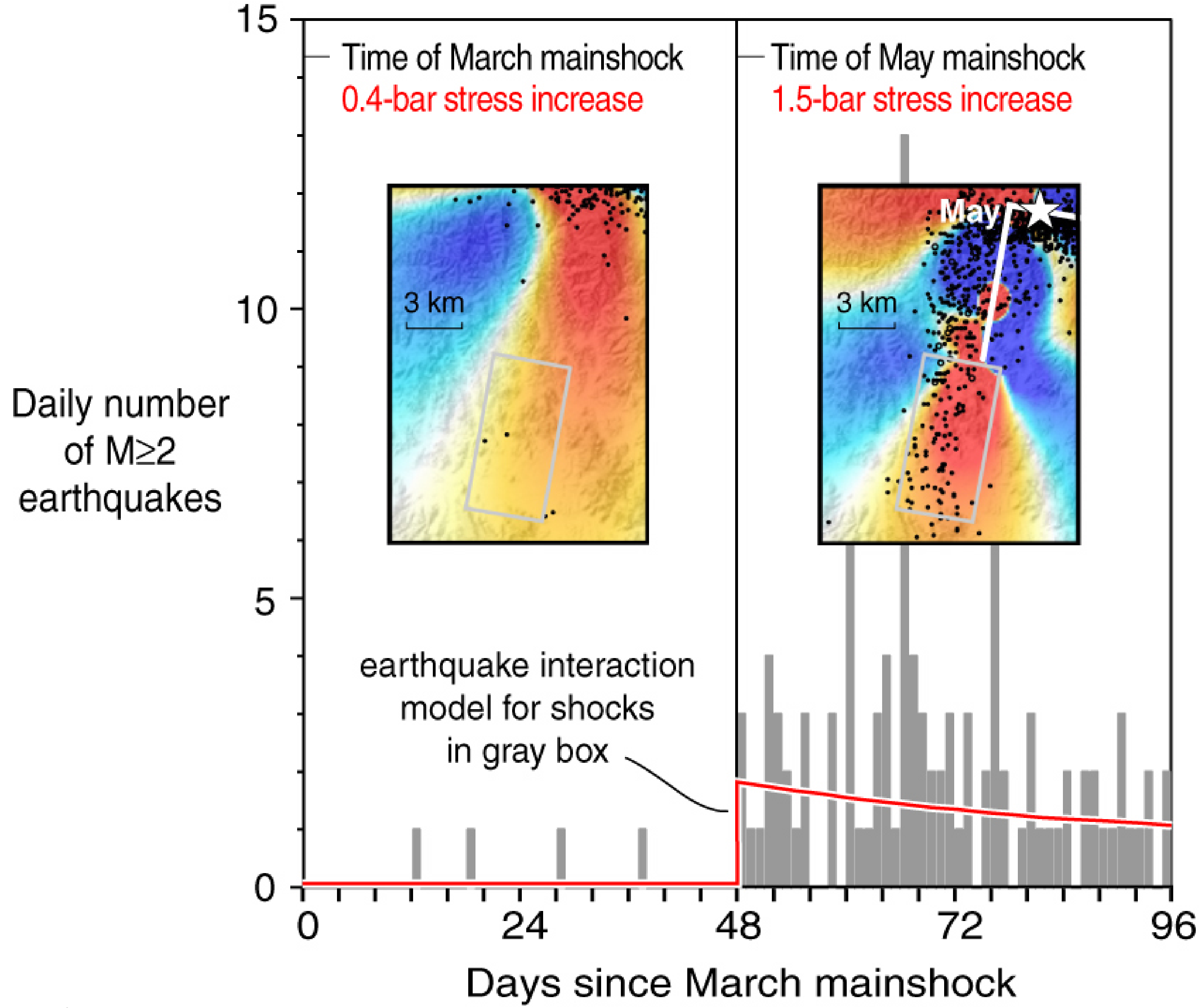



The seismicity rate jump and decay can be matched by a rate/state model

**Toda & Stein, 2003**

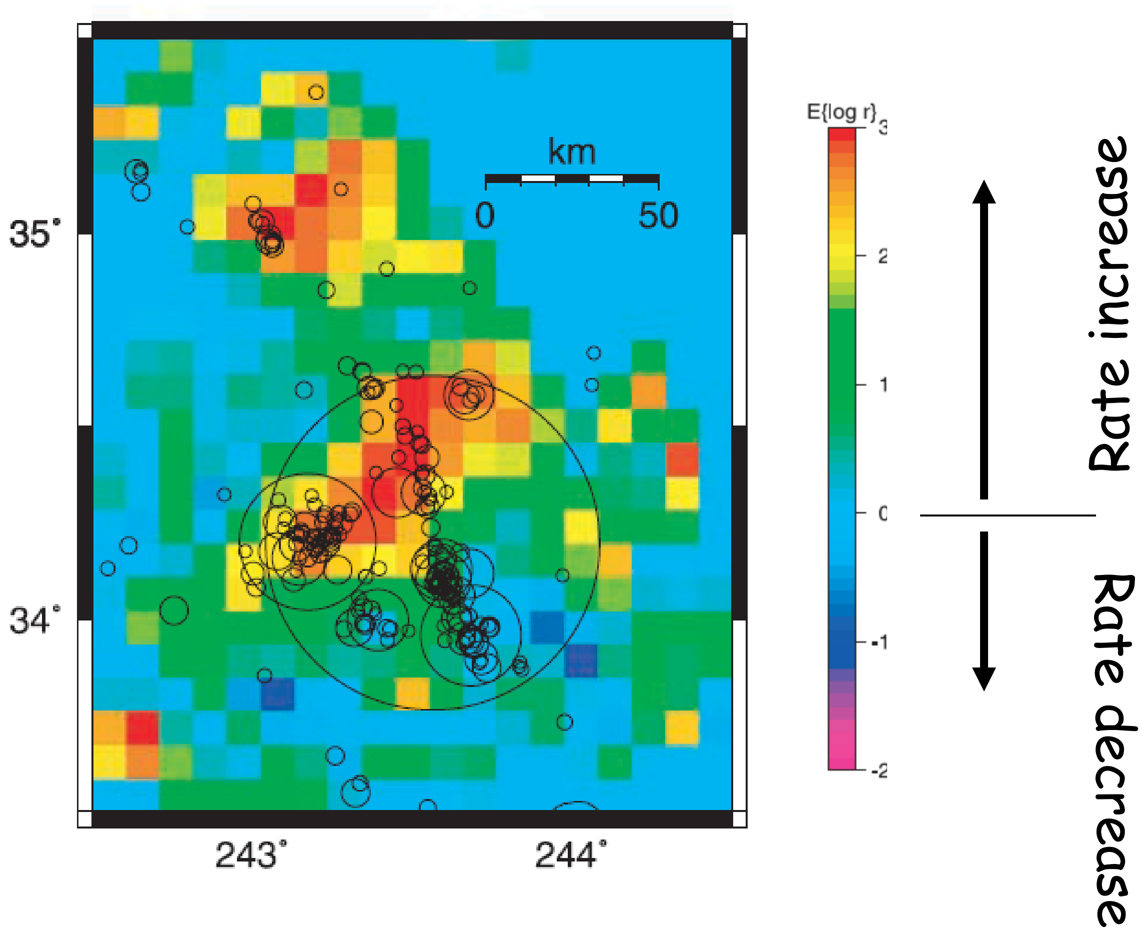



Toda & Stein, 2003




**Toda & Stein, 2003**

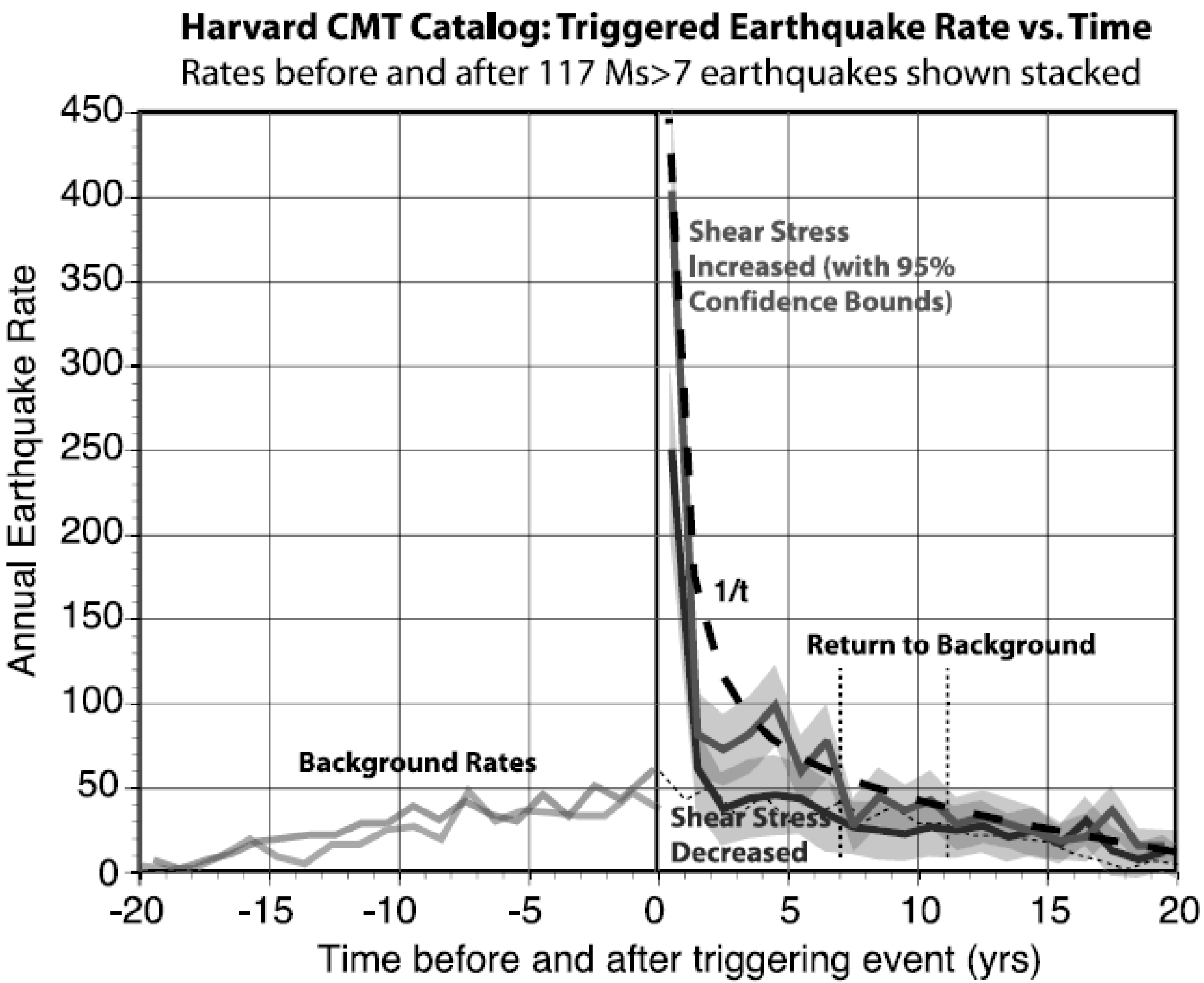
# Existence and persistence of stress shadows are still controversial issues




First 100 days following Landers

Marsan (2003)

# Earthquakes that underwent ΔCFF<0 still occur at higher rates after the mainshock than before…




Parsons (2002)

**No or too few shadows immediately after the mainshock (i.e., they can eventually show up after a delay):**

| | |
|---|---|
| Parsons (2002) | Global |
| Marsan (2003) | Landers, Loma Prieta, Northridge |
| Toda and Stein (2002) | Coalinga |
| Felzer and Brodsky (2005) | Loma Prieta |
| Ma et al. (2005) | Chi-Chi |
| Daniel et al. (2006) | Izmit and Duzce |
| Mallman and Zoback (2007) | Landers, Kobe |
| Daniel et al. (2007) | Doublet Iceland June 2000 |

**Observations of instantaneous quiescences:**

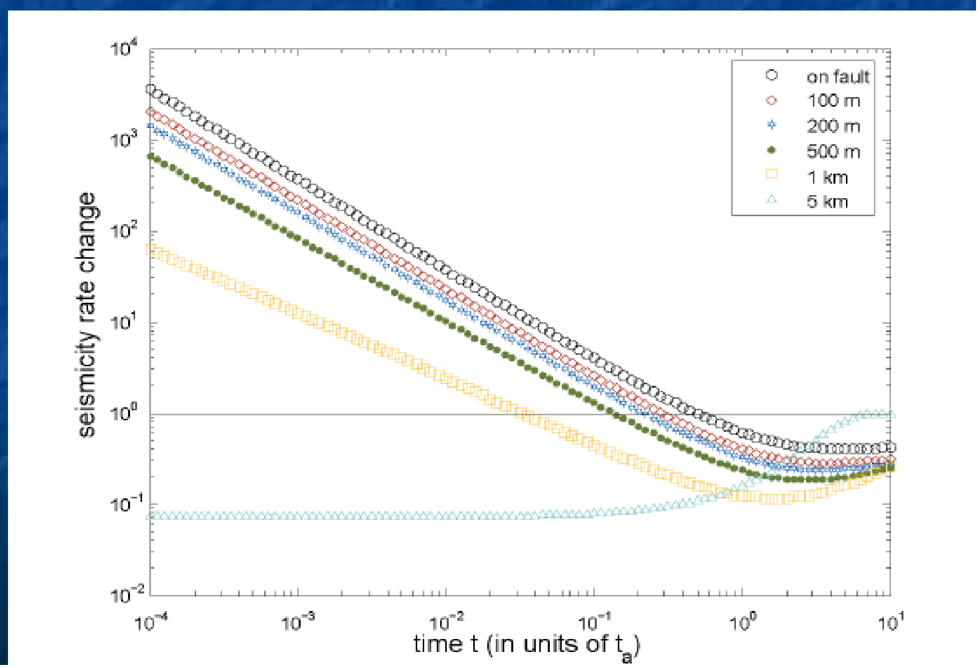
| | |
|---|---|
| Dieterich et al. (2000) | Kilauea |
| Toda and Stein (2003) | Kagoshima |
| Woessner et al. (2004) | Kagoshima |

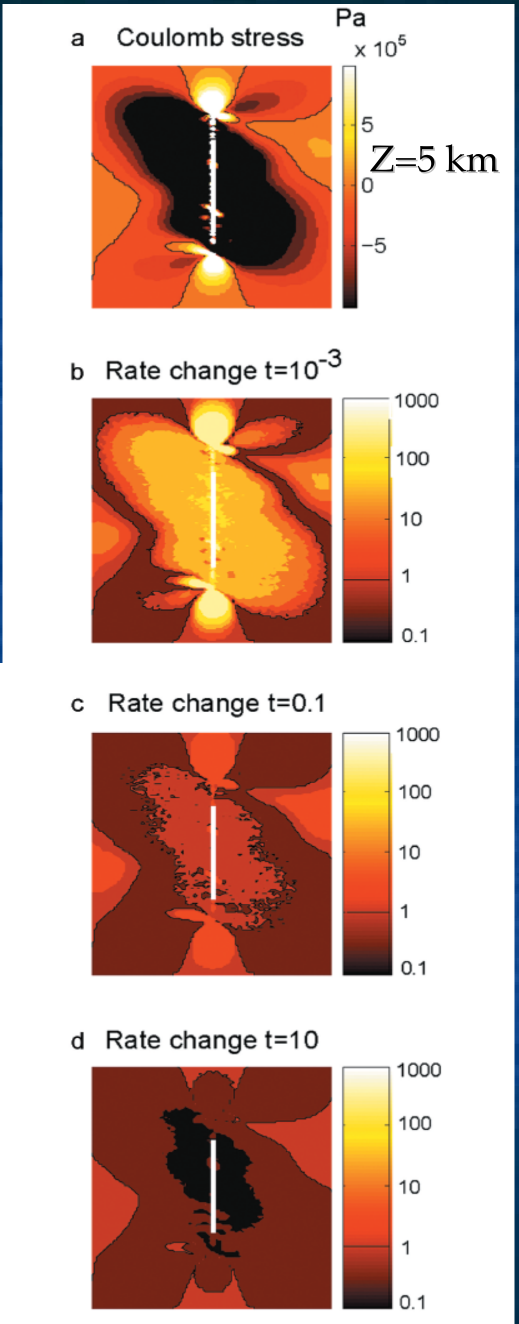
# Stress Heterogeneity

Paucity of detectable seismicity shadows

- Dynamic triggering
- Secondary triggering

Marsan (2006) proposes that spatial heterogeneity of coseismic stress change also contributes to reduce seismicity shadows on faults & off-fault




see also Helmstetter & Shaw, JGR, 2006

from D. Marsan, JGR, 2006

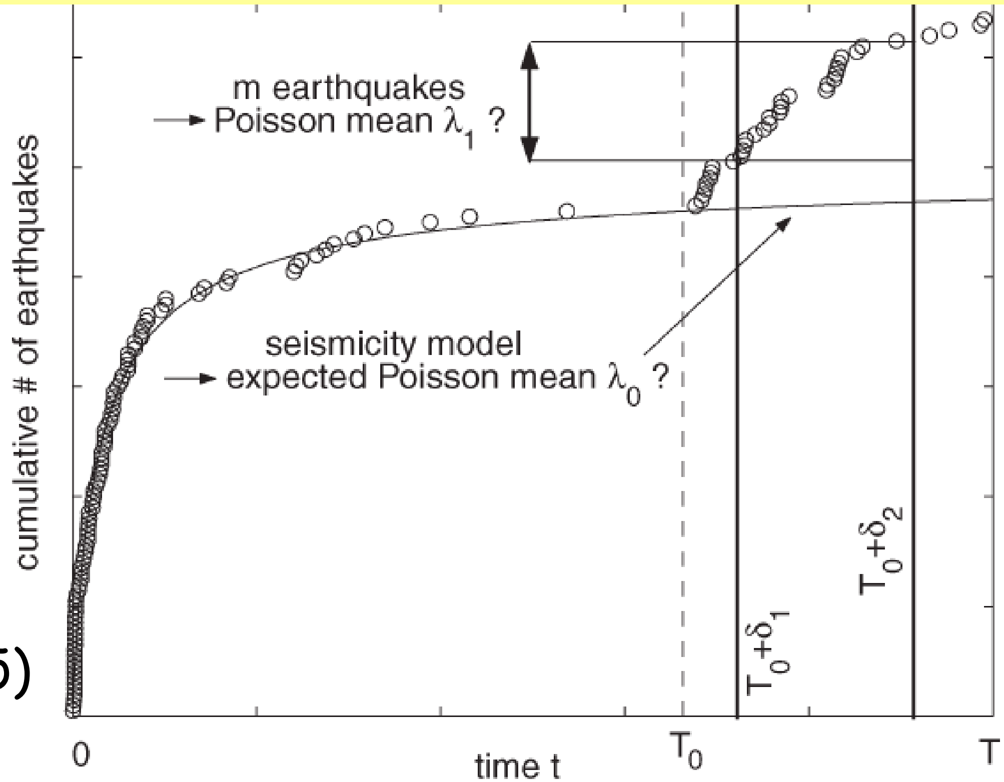
# Measuring Rate Changes

**To account for the non-stationarity of seismicity time series:**

• a model is fitted to the time series up to mainshock time $T_0$

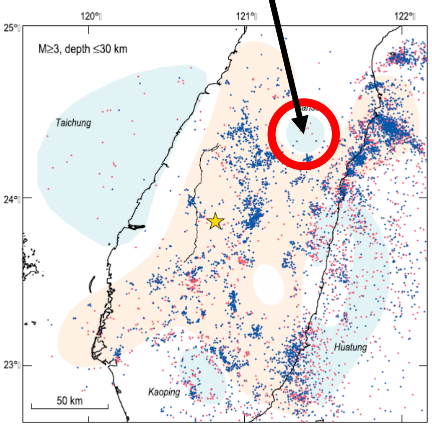
• this model is extrapolated to predict what should have happened had the mainshock not occurred

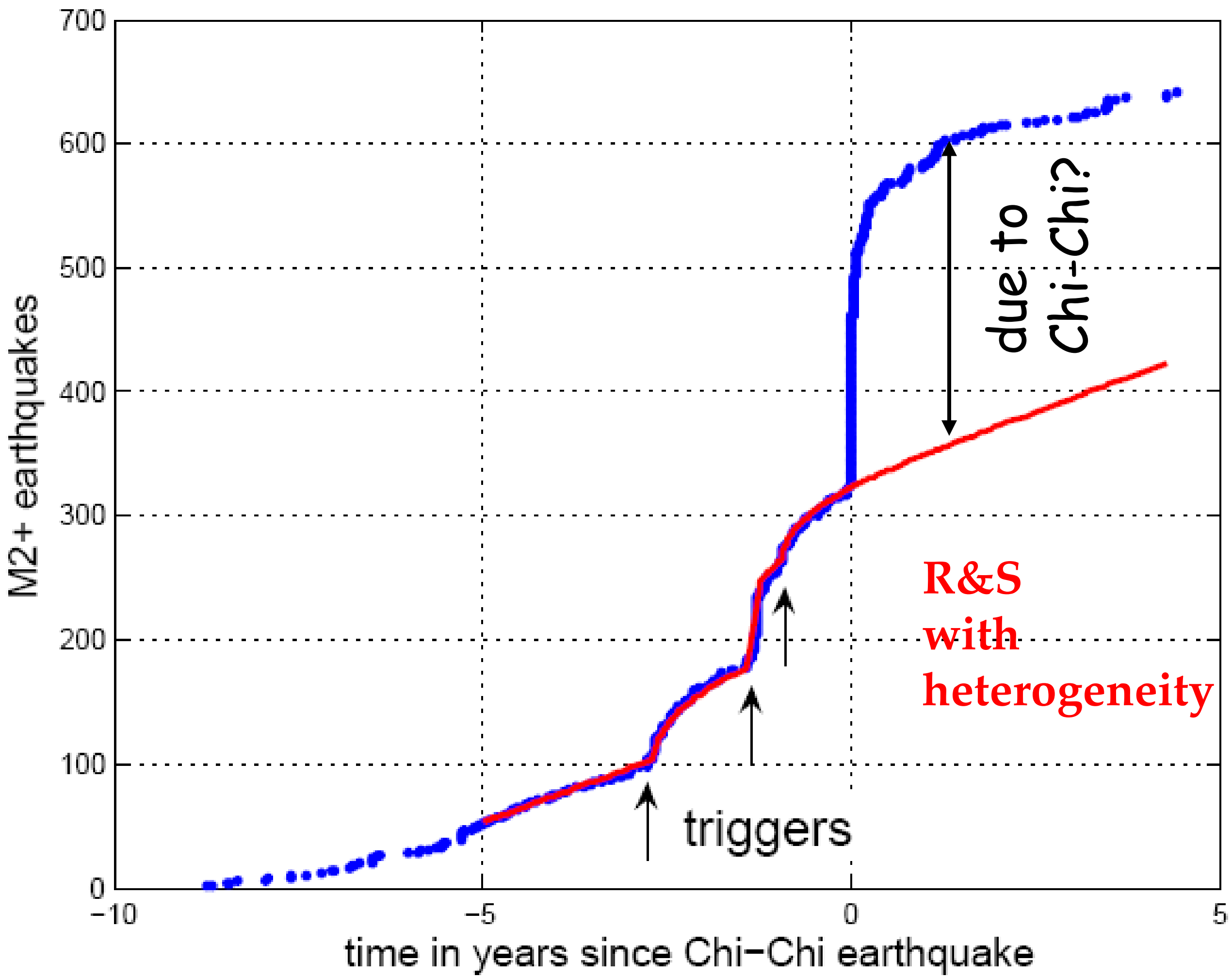
• this extrapolation is compared to the observed number of earthquakes




Marsan and Nalbant (2005)

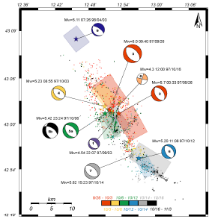
**An example:** rate increase following Chi-Chi in a small zone (Nansan), using a rate-and-state model with stress heterogeneity.

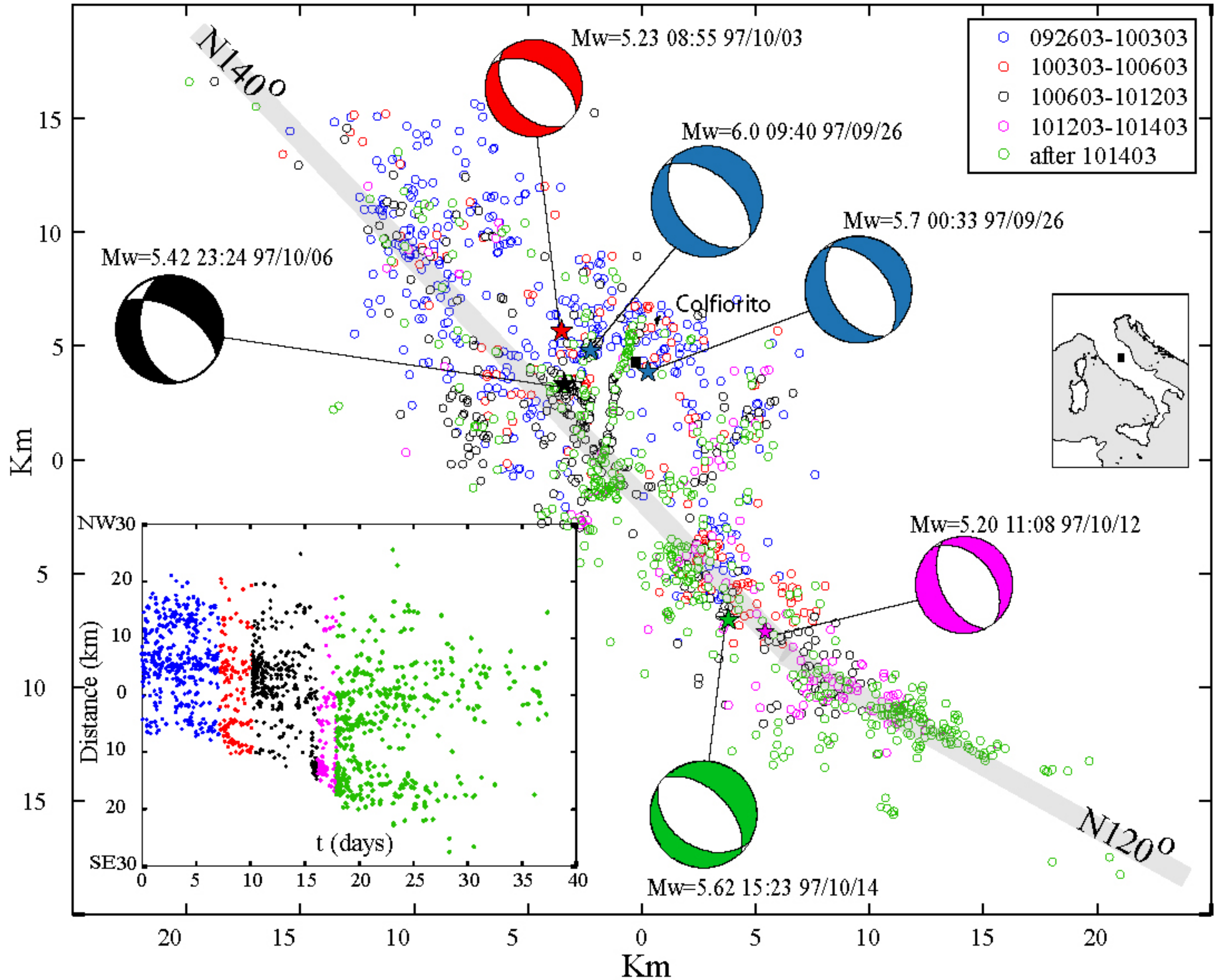



Marsan & Daniel (JGR in press)

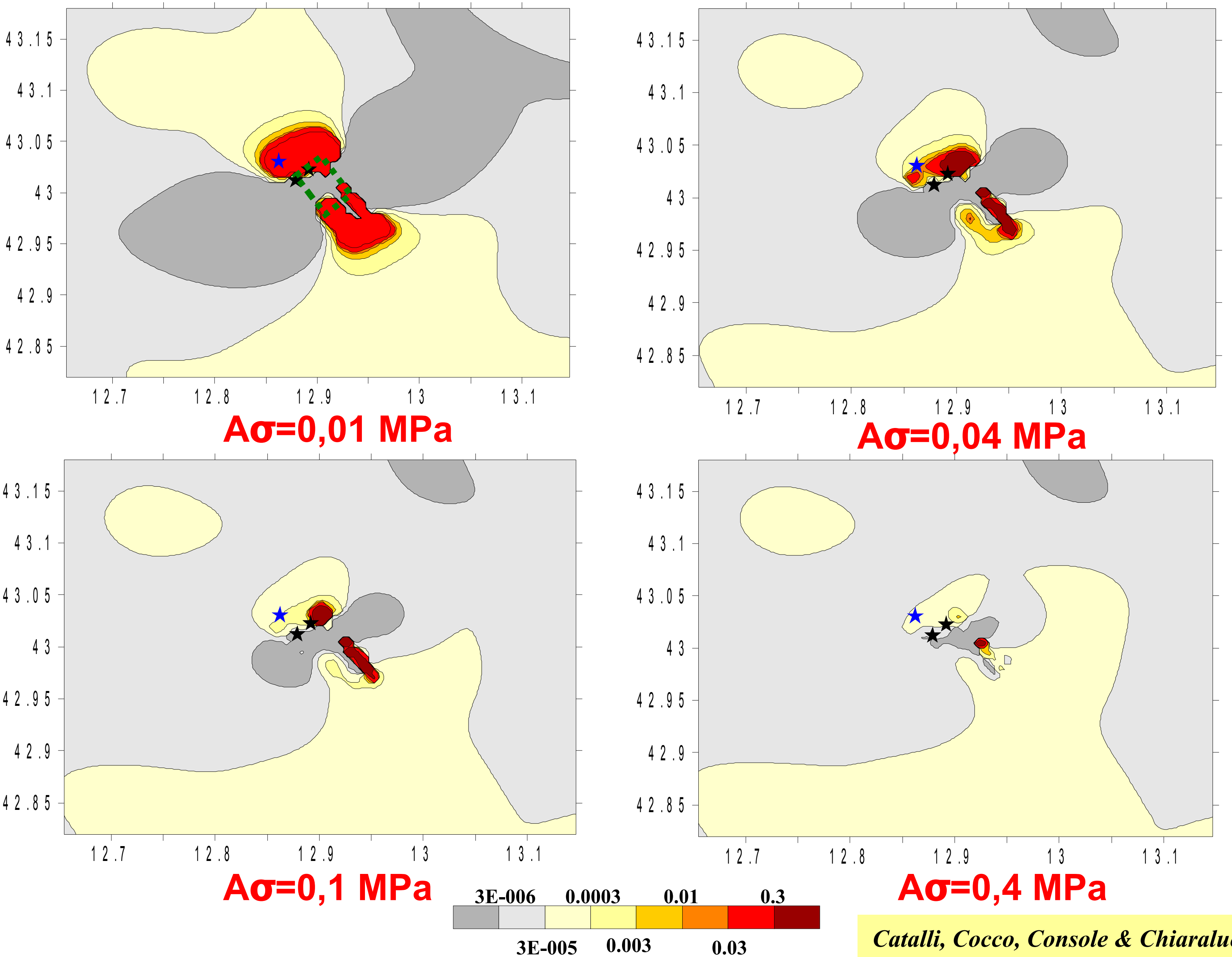
# The Colfiorito sequence



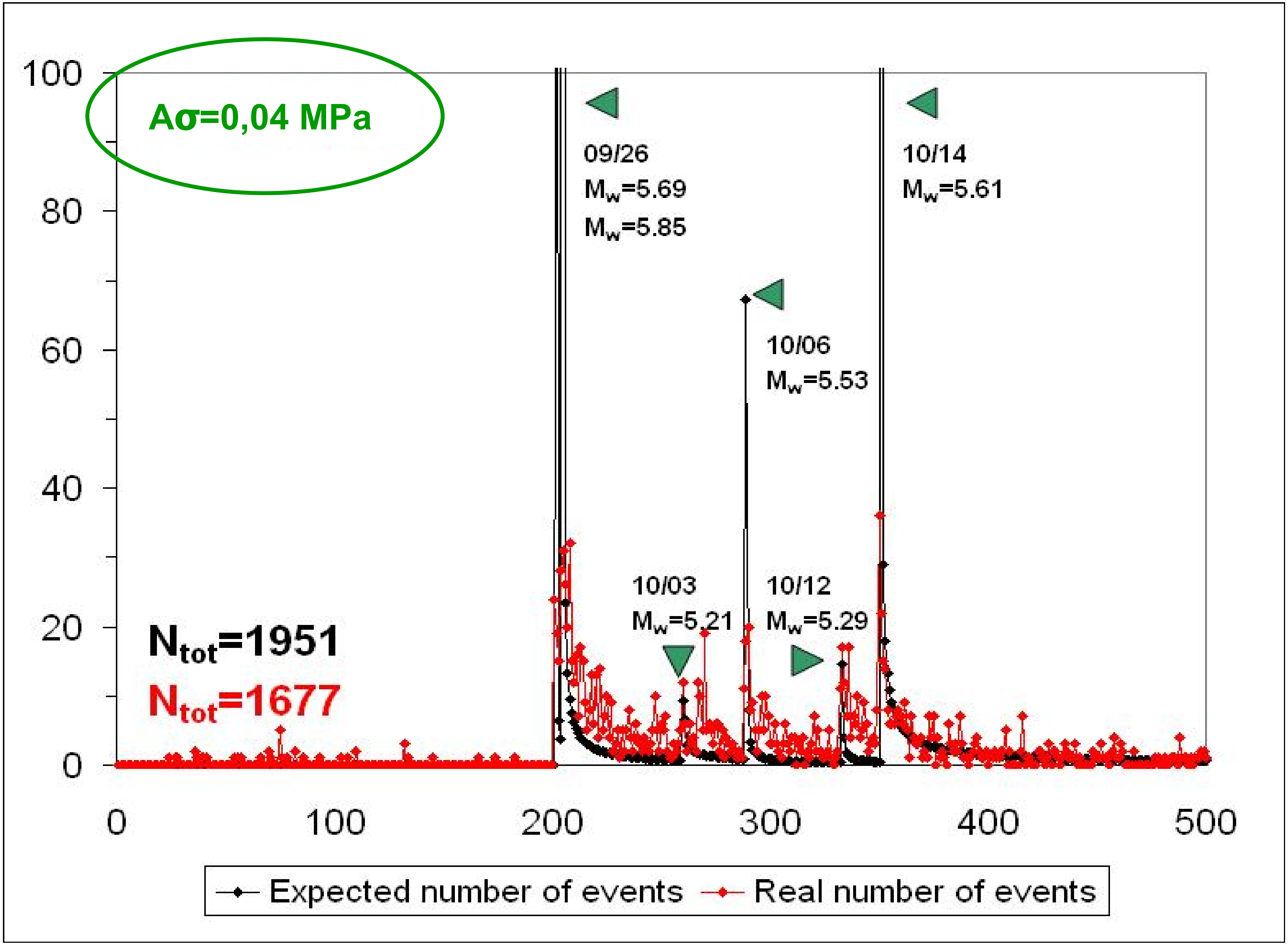


# Effects of using different Aσ

**26/09/97 09:41**

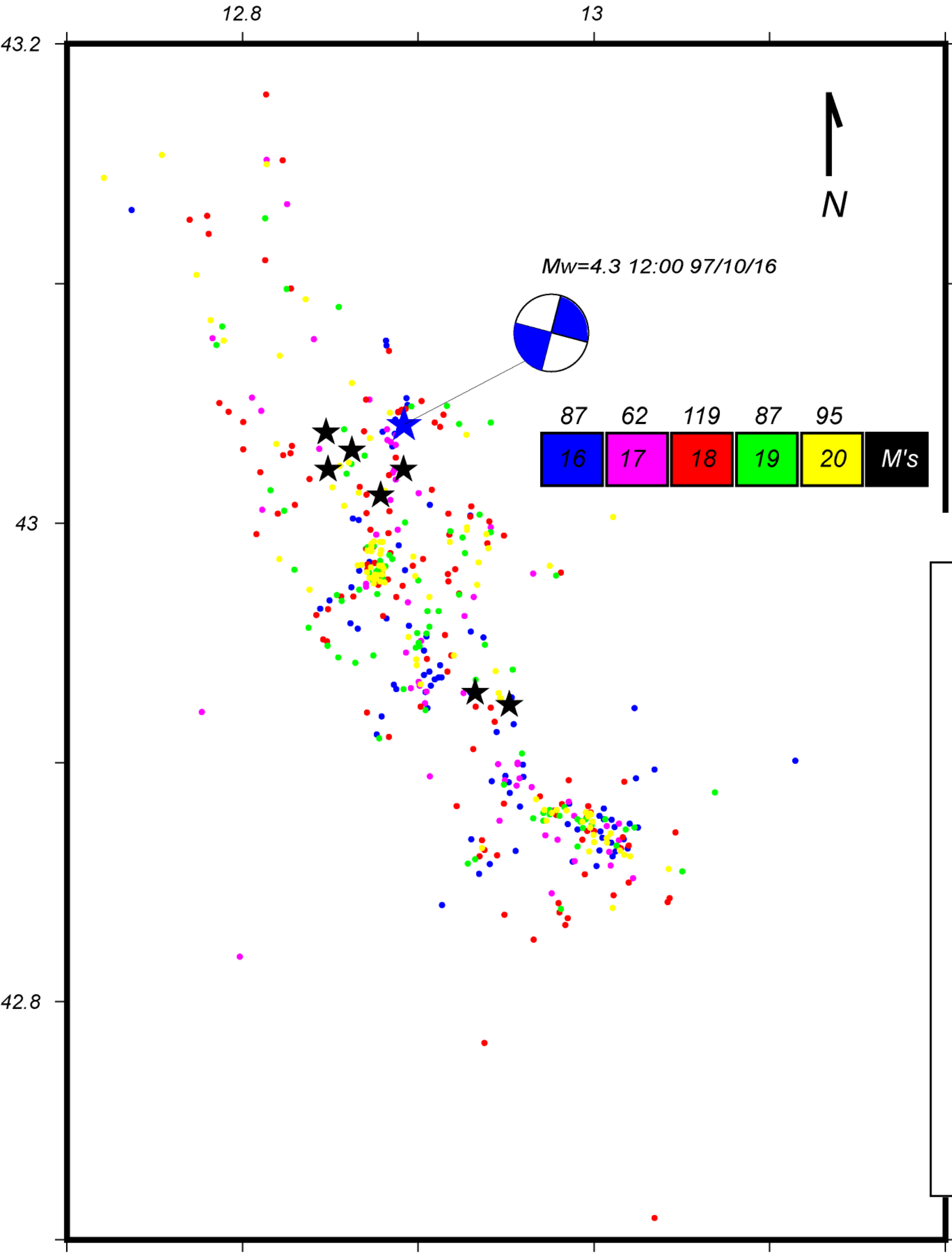


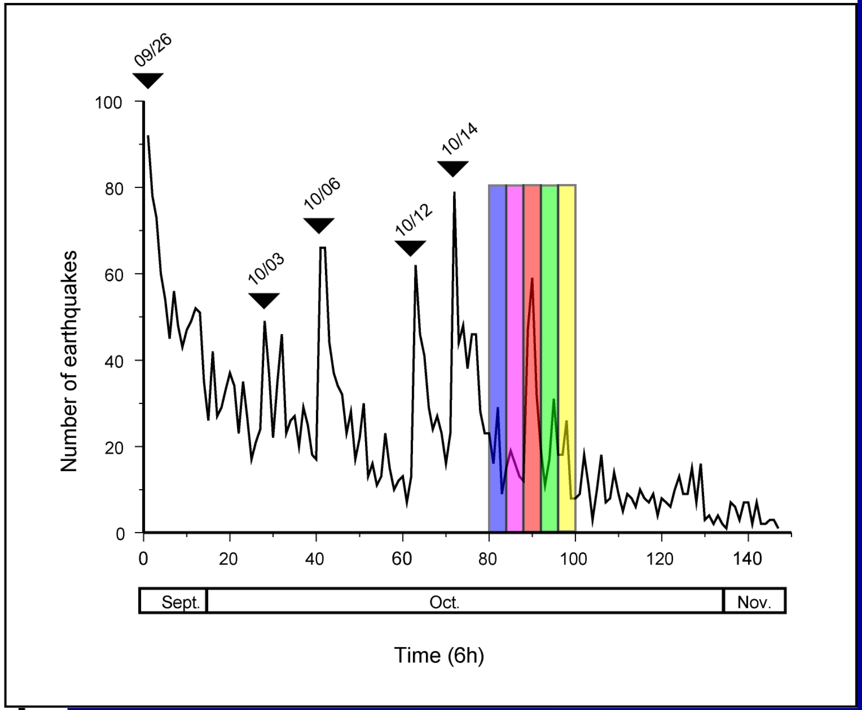

*Catalli, Cocco, Console & Chiaraluce*, in prep.



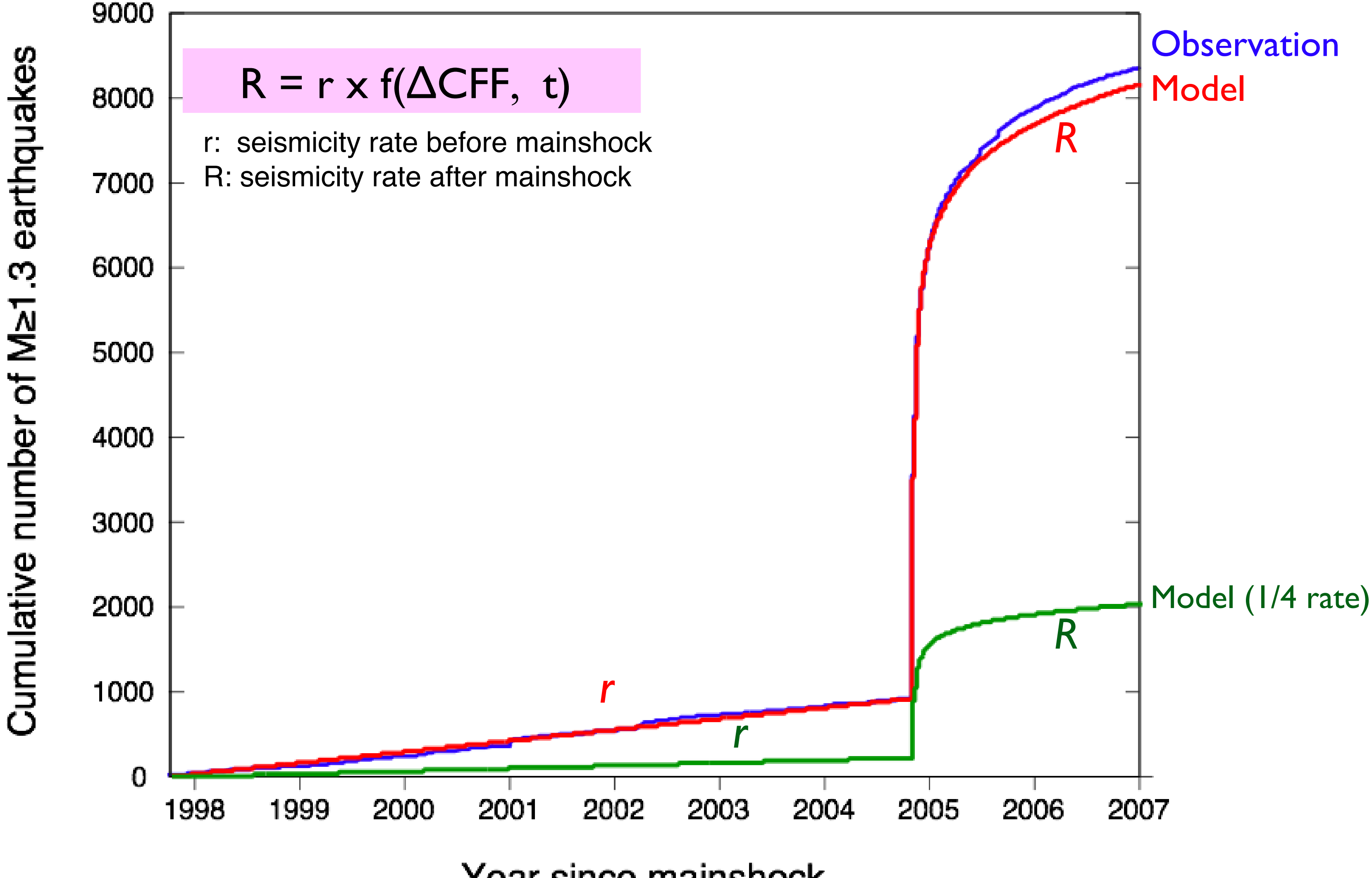

*Catalli et al*., in prep.

# An increase of seismicity rate not caused by any main shock



# The effect of the reference seismicity rate
# Niigata earthquake 2004 (Japan)




Courtesy of Shinji Toda

# Probability calculation

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- A conditional probability model for the occurrence of an earthquake on a single fault between elapsed times $t_e$ and $t_e+\Delta t$

$$P_c(t_e < T < t_e + \Delta t \mid t_e < T) = \frac{\int_{t_e}^{t_e+\Delta t} f(T)\,dT}{\int_{t_e}^{\infty} f(T)\,dT} = \tilde{f}(T)$$

- A seismicity rate probability model for a fault population

$$P = 1 - e^{-N}$$

- Process with memory
- Non-stationary
- Clustered at least in space

$$N = \int_{t_e}^{t_e+\Delta t} \lambda(t)\,dt \qquad \lambda(t) = R(t)\beta e^{-\beta(m-m_o)}$$

# Interaction Probability: the effect of an applied stress step

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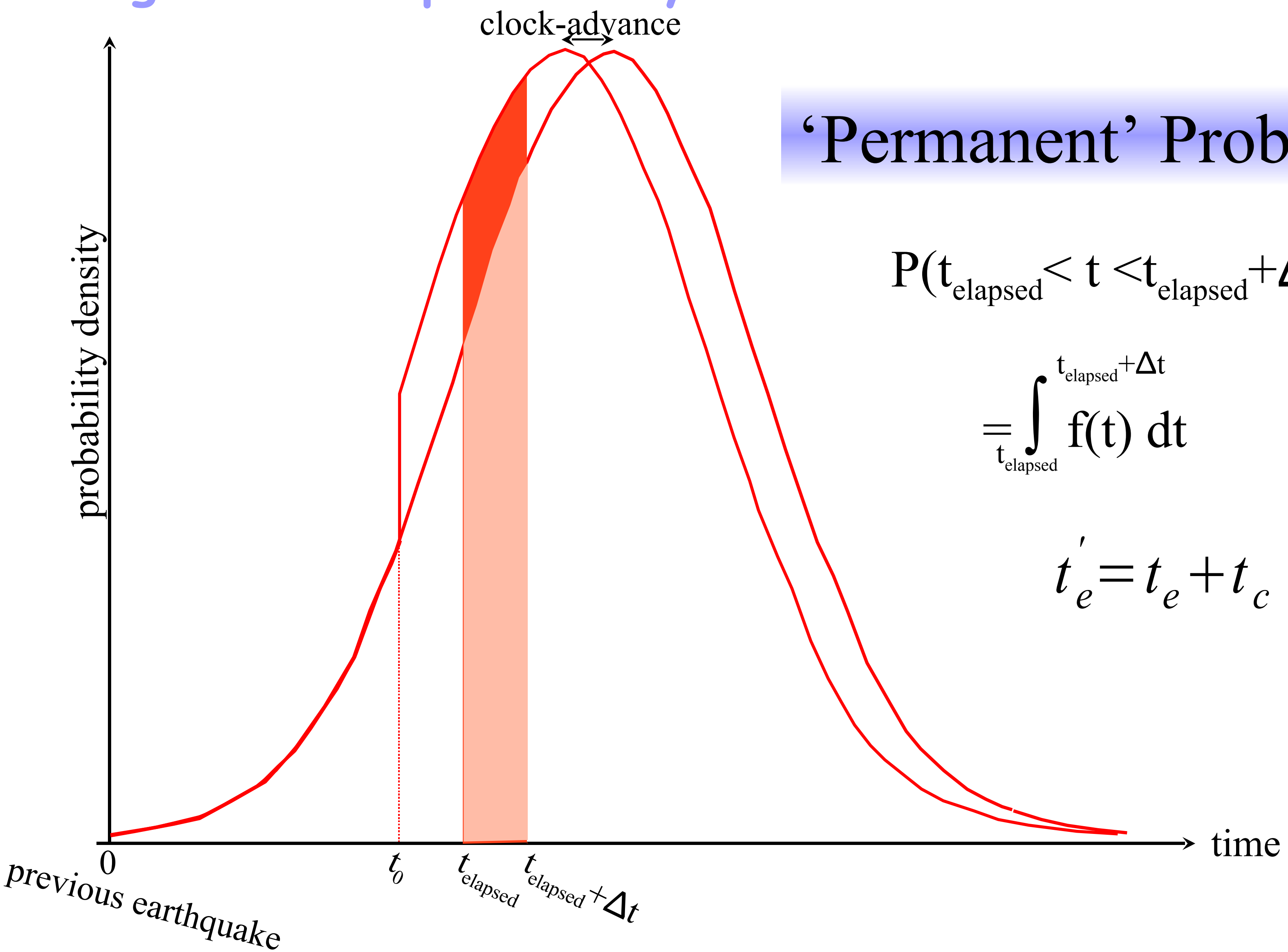
- Maturity and frictional properties are neglected (Coulomb model):

$$t_{Coulomb} = \frac{\Delta\tau}{\dot{\tau}} \Rightarrow \begin{aligned} t_e' &= t_e + t_{Coulomb} \\ T' &= T - t_{Coulomb} \end{aligned}$$

$$P_c\left(t_e < T < t_e + \Delta t \mid t_e < T\right) = \tilde{f}\left(T'\right)$$

# Single Fault : probability of failure after a stress step




## 'Permanent' Probability

$$P(t_{elapsed} < t < t_{elapsed} + \Delta t) =$$

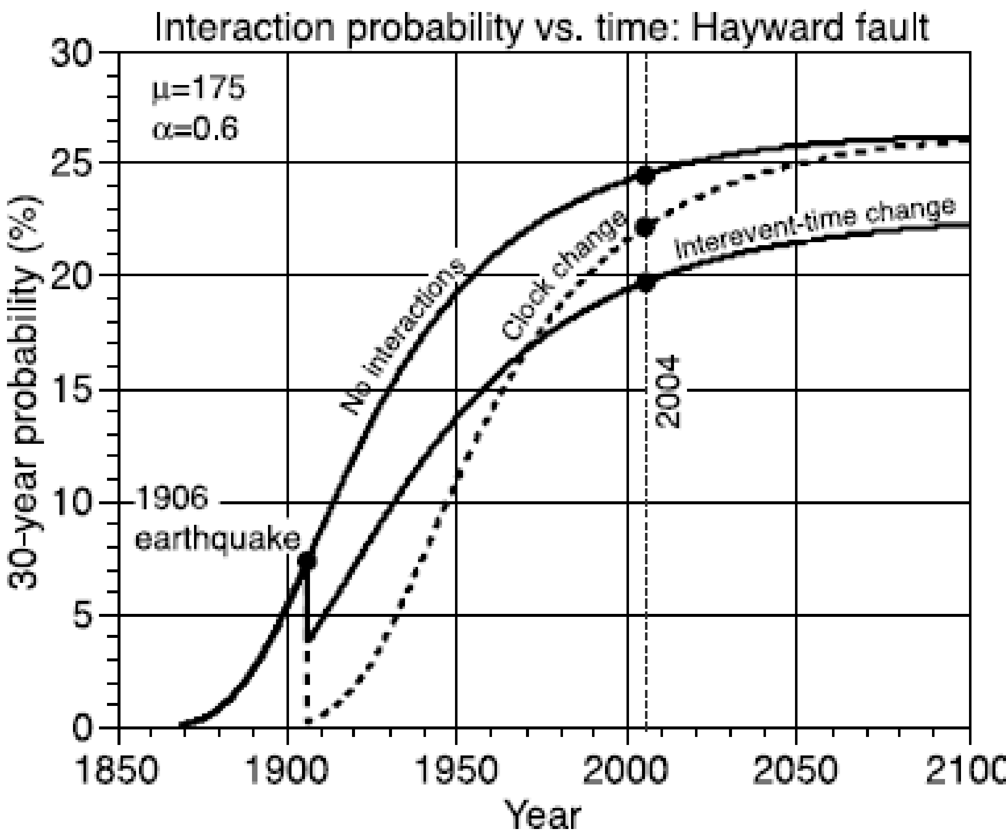
$$= \int_{t_{elapsed}}^{t_{elapsed}+\Delta t} f(t)\,dt$$

$$t_e' = t_e + t_c$$

Clock-advances shorten the mean recurrence time, increasing the probability.

# The two choices yield different results

- 30-year conditional probability versus time on the Hayward fault (CA) after a imposed 0.5 MPa stress decrease caused by the 1906 earthquake.
- Clock change = elapsed time has been reduced (time of the last earthquake was set forward
- Interevent-time change = recurrence time was lengthened by an amount proportional to the stress change




$$t_{Coulomb} = -\frac{\Delta CFF}{\dot{\tau}} \Longrightarrow \quad t_e' = t_e - t_{Coulomb}, \quad T' = T + t_{Coulomb}$$

Parsons, 2005

# The effect of an applied stress step

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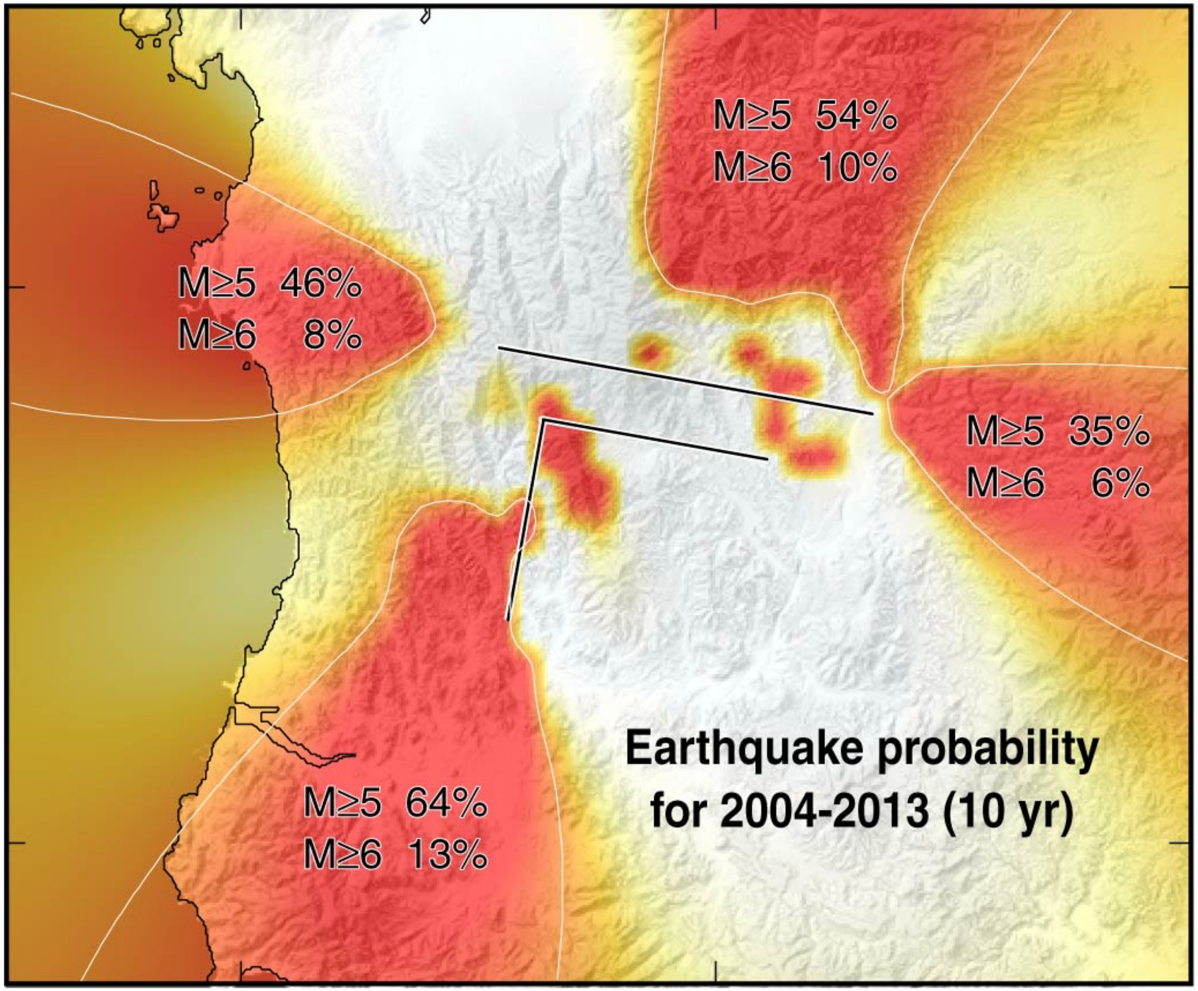


Rate/State seismicity model

Toda & Stein 2003 JGR

0 5 10
km

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# More complex (and controversial) is to include seismicity rate changes in a renewal process characterized by a conditional probability

- But this has been done → Stein et al. (1997) who applied it first to the Istanbul area;
- Other studies (Parsons et al., 2000; Hardebeck, 2004; Parsons, 2005; Gomberg et al., 2005) discussed this approach in detail

# "Interaction" Probability

$$P(t_{elapse} < t < t_{elapse} + \Delta t) = 1 - \exp\{ - \int_{t_{elapse}}^{t_{elapse}+\Delta t} R(t)\, dt\}$$

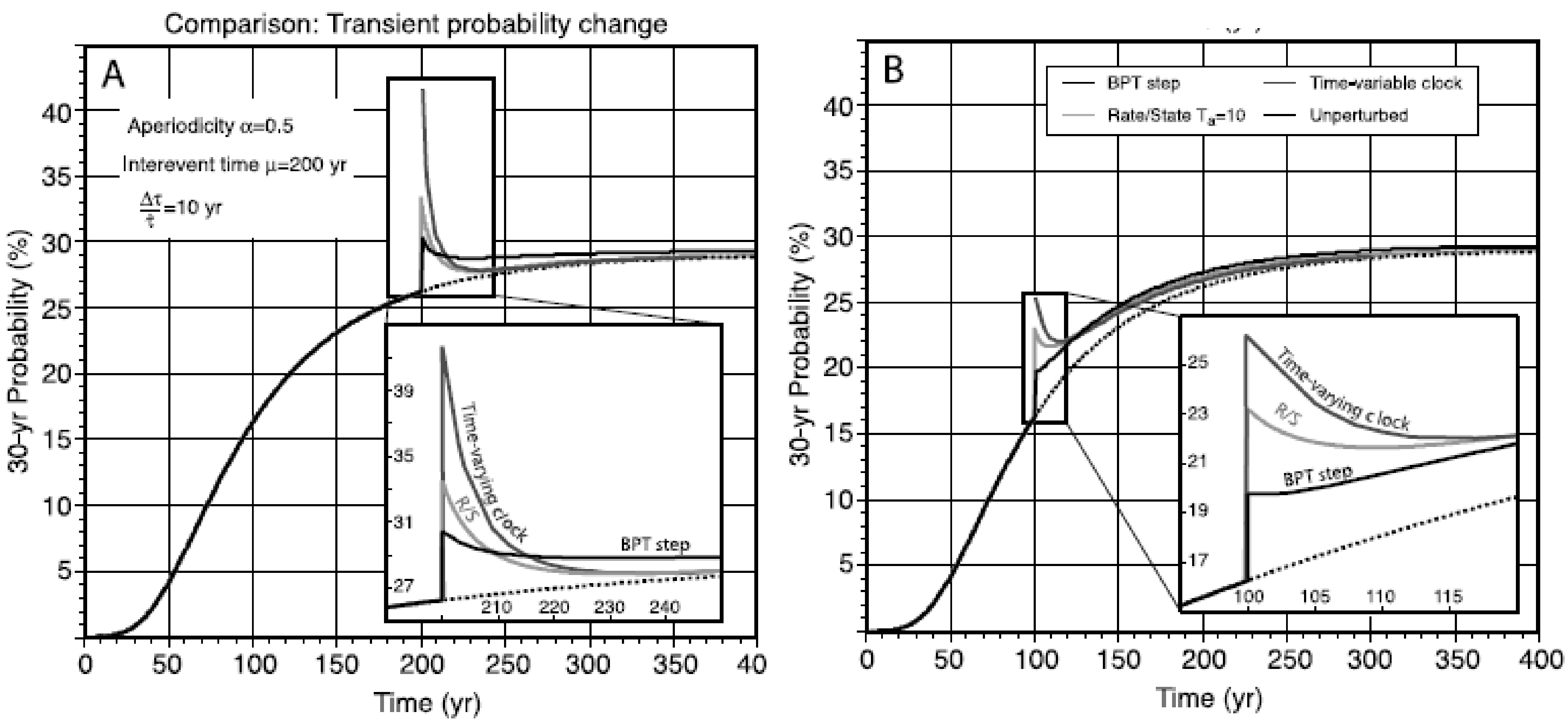
$$= 1 - \exp\{-N\}$$

R(t) = Rate Change

$$N = r\left\{\Delta t + t_a \ln\left[\frac{1+\left[\exp\left(^{-\Delta\tau}\big/_{A\sigma_n}\right)-1\right]\exp\left[^{-\Delta t}\big/_{t_a}\right]}{\exp\left(^{-\Delta\tau}\big/_{A\sigma_n}\right)}\right]\right\}$$

$$N = r(t_o)\cdot\left\{\Delta t + F\left[\Delta t, t_e - t_o, \Delta\tau, A, \sigma_n\right]\right\}$$

# Permanent and Transient probability following a stress step




**Δτ = 0.1 MPa**

Parsons, 2005

Interevent time 100 yr

# Implications

- The permanent probability depends on the time of application of the induced perturbation ($t_o$) through the equivalent Poissonian rate $r(t_o)$.
- The transient probability does not depend on the time passed since the last earthquake $t_e$, but only since the perturbing earthquake ($t_e$- $t_o$).
- The evolution toward failure (conditional nature of the process) is not accounted in the transient probability change.
- Incorporation of stress transfer in earthquake probability calculations can be justified for stress changes much larger than the stressing rate: this means large earthquakes and close distance from causative faults

# Open Questions to be discussed

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- Existence and persistence of stress and seismicity shadows
- Role of input parameters in physically-based models for seismicity rate and probability calculations ($A\sigma$, r, …)
- Use of physically-based models
- Measure and definition of the reference or the background seismicity rate
- Significance of interaction probability
- Validation of physically-based models for practical and near-real time applications